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Performance Optimization of a Farm-Scale Direct-Fired Biomass Furnace

FINAL REPORT

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Prepared for

MONTANA DEPARTMENT of NATURAL RESOURCES and CONSERVATION

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PERFORMANCE OPTIMIZATION
OF A
FARM-SCALE DIRECT-FIRED BIOMASS FURNACE
FINAL REPORT

Prepared by

✓ Bruce Kinzev, GRA
✓ Dr. W.E. Larsen

Montana State University
Agricultural Experiment Station
Agricultural Engineering Department
Bozeman, Montana 59717
(406) 994-2275

Prepared for

Montana Department of Natural Resources and Conservation
1520 East Sixth Avenue
Helena, Montana 59620-2301

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PERFORMANCE OPTIMIZATION
OF A
FARM-SCALE DIRECT-FIRED BIOMASS FURNACE

Final Report

1. The parties involved in this project were:
 - a. The Agricultural Engineering Department, Montana State University, Bozeman, Montana, 59717, (406)-994-2275.
 - b. The Montana Department of Natural Resources and Conservation, Helena, Montana, 59601. (406)-444-6697
 - c. The Southern Agricultural Research Center, 748 Railroad Highway, Huntley, Montana, 59037, (406)-348-3400.
2. The people to contact concerning this project are:

Dr. W.E. Larsen, 409 Cobleigh Hall, Montana State University, Bozeman, Montana, 59717. (406)-994-2275.

Dr. Gil Stallknecht, 748 Railroad Highway, Huntley, Montana, 59037. (406)-348-3400.
3. The biomass furnace used in this project is located at the Southern Agricultural Research Center in Huntley, Montana.
4. The total budget for the project amounted to \$18440, to this date the amount used out of this budget is \$18055.75.
5. This project was funded to research use of renewable fuels as a means of reducing Montana's dependence on conventional fuels. The study was centered on the use of a direct combustion grain dryer burning renewable fuels. The fuels used in the study were corn cobs and corn stover, winter wheat straw, wood chips, and sawdust. Economic estimates were generated to determine the best system for particular sites.

Abstract

A commercially-manufactured direct combustion biomass furnace system was purchased and assembled by the Montana State University Agricultural Engineering Department for the purpose of evaluating the feasibility of using biomass fuels in Montana. Common biomass fuels in Montana include wheat straw and wood by-products from sawmills. The furnace used in the research had to be modified to use the full range of biomass fuels common in Montana. The original system was intended for corn cobs and corn stover only. Further modifications to the original system included the addition of an air-to-air flat plate heat exchanger and a microprocessor-controlled air tempering device.

Many extra costs were encountered with these system modifications, and it was determined that retrofitting an existing system will generally not return economic rewards. Experiences with these modifications made it evident that a successful biomass system requires careful initial design and manufacture for the specific fuel that will be used.

It was determined that a biomass system designed for Montana should be usable with straw and/or wood chips, ideally for both. The optimal system design will depend on the individual situation.

Biomass systems can return economic rewards if the fuel and system design are carefully matched.

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Introduction

A biomass-fueled grain dryer was purchased and assembled by the MSU Agricultural Engineering Department at the Southern Agricultural Research Center (SARC) in Huntley, Montana, to investigate the feasibility of biomass as an alternative fuel source for Montana. Little (1984) found that use of the biomass for fuel required extra labor and caused problems not encountered with conventional fuels. Little's comparison fuel was propane, and his conclusion was that it was not then economically feasible to use a biomass system in place of a propane system.

The purpose of the current research was to investigate whether the existing biomass burner could be modified to improve its performance and reduce its operating costs to less than those of a conventionally-fueled system. Modifications to the biomass system included a microprocessor-controlled air tempering mechanism, a heat exchanger, and changes to the fuel feeding system.

The general findings of the study were that the attempted modifications or retrofits to the existing system did not bring economic returns because of unique construction and adaptation costs, and generally limited benefits from the changes.

Experiences with the system have generated ideas on the fuel and design requirements for an optimum biomass system. It is known that several of the economic and technical problems encountered with the SARC system could be avoided through different circumstances and system designs. Specification of these requirements and suggested future research is included in this report.

Mass, Energy, and Flow Diagram

Figure 1 shows the flows of mass and energy for a generic biomass system. Different systems may have differing individual flows. The combine separates the corn as grain from the cobs and stalks in the field. The cobs and stalks are then air dried and burned to dry the corn grain.

Equipment Specifications

Many problems arose from the substitution of biomass feedstocks other than those the system was originally designed for. The SARC system was designed in the midwestern United States, where corn is grown abundantly and corncobs are a readily available fuel source. Winter wheat straw was determined to be a much more suitable biomass fuel source in Montana because of its high availability. Straw also has a much lower collection cost than corncobs, and often has little alternative value. Use of straw in the SARC system resulted in plugging of the auger feeding mechanism, which was intended for corncobs.

The main requirement for a biomass system to be used in Montana is that it be suitable for using straw as fuel. It does not appear wise to restrict a system to any particular fuel, however, so an optimum system should also be usable for other fuels.

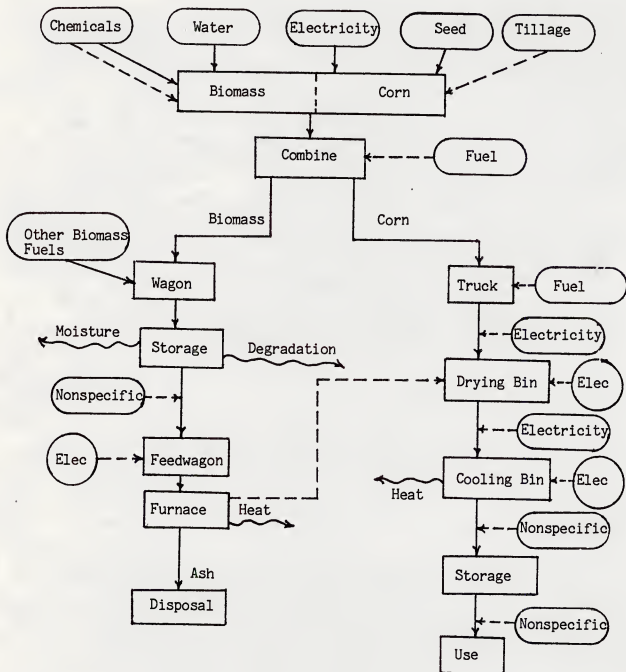


Figure 1. Energy, Mass, and Flow Schematic. "Nonspecific" may be one or more different forms of energy.

Unprocessed straw will not feed well with an auger type of feed mechanism. Straw commonly causes problems with wrapping and plugging in rotating system components. Use of straw in a biomass furnace system will require either processing to make it less prone to feeding problems or a different overall system design that does not use a continuous feed system.

Cubing or grinding straw and other fuels makes them more uniform and improves their feeding characteristics. Part of the feeding problem with straw is that its length allows it to completely wrap around auger blades or catch on stationary surfaces. Reducing its length to a few inches will nearly eliminate both of these problems. Cubing or pelletizing biomass fuels makes them very uniform and free flowing so that different materials can be easily used in the same system. The density of cubed materials is relatively high so that more fuel can be placed in the feed hopper which will reduce some furnace stoking labor. Processing the biomass represents energy and capital inputs to the user, and so may not be the most desirable alternative in all situations.

An enclosed combustion chamber furnace design appears to be a logical option for the use with straw. No mechanical feeding system is used, because the entire fuel batch is placed into the combustion chamber prior to firing of the furnace. Fire danger and therefore required supervision is also greatly reduced because the flame is completely contained within a closed chamber. There are no rotating or other mechanical parts to become plugged with straw or other fuels. Less equipment is required to purchase, maintain, and operate these systems. This system design has in the past had lower operating efficiencies than other designs because the amount of excess air present in the chamber dramatically increased as the combustion of the fuel batch neared completion. Newer designs are correcting this problem with automatic controls on the inlet air valve. Manufacturer's literature reports operating efficiencies as high as 85 percent.

Various studies with biomass gasifiers (or two-stage burners) indicate that the particulate levels in the exhaust are much less than those in one-stage furnaces like the one installed at the SARC. This is because most of the flyash and particulates are burned in the second stage of combustion. A gasifier used for grain drying would not require a heat exchanger for grain drying and would rarely if ever result in a reduced grade. A gasifier would also be better for structural heating, even though a heat exchanger would be required, because there would be less fouling of the heat exchange surfaces due to the reduced particulate levels in the exhaust. The combination gasifier/enclosed combustion chamber design appears to currently be the best system design, systems of this type are commercially available.

Economics

Equipment costs, extra labor, and other possible uses for biomass are the principal factors affecting the economic feasibility of biomass.

A biomass fueled drier requires more equipment than a propane drier. The additional equipment and installation charges for this equipment totaled more than \$13000 for the SARC system. The first economic obstacle a biomass system must overcome is this initial debt incurred as a result of choosing biomass as the fuel source. When 6 percent interest is included over an assumed ten year system life, an

annual fuel savings approaching \$2000 is needed just to pay off the initial cost of the system.

Labor is relatively expensive. Any extra labor required for a biomass system quickly increases the costs of using that system. Depending on the wage rate, the labor charges for supervising the operation of a system can equal or even exceed the fuel costs. Conventional fuels generally require little or no supervisory labor; virtually all the labor required for using biomass represents additional cost that directly reduces the fuel savings over conventional fuels. Labor associated with harvesting, handling, and transporting the biomass will always be required; these labor charges are directly accounted for in fuel cost estimations and represent reasonable costs. However, in most situations the biomass fuel savings will never pay off if the system must be constantly supervised during operation.

Another substantial cost of using biomass as fuel is the loss of the value of the material for other purposes. The opportunity cost for using the biomass for fuel probably ranges in most cases between 0 and \$25/ton. Possible fuel materials such as alfalfa would have an opportunity cost much higher than this range, and would never be logically used as a fuel source. Biomass materials which have little or no alternative value make the best choice as feedstocks from the opportunity cost standpoint. Materials such as wet or moldy hay, while having no alternative value, may still not be usable as fuel due to their high moisture level.

Computer Program

A BASIC computer program intended for preliminary analysis of biomass system feasibility has been written by the MSU Agricultural Engineering Department, and is included with this report. The program is for an IBM PC or compatible equipment. It can be used by anyone contemplating the use of a biomass furnace system. The program is designed to estimate system and operating costs, and make comparisons with conventionally-fueled systems. A payback cash flow table and external rate of return estimation are generated to provide the user with preliminary investment evaluation information. The program is not intended for use as an exact predictor of costs and returns for an individual; but rather to provide enough information for deciding whether further investigation of the biomass alternative is justified. User input includes whether the system is to be used for drying grain or for heating the space in a structure. Information needed also includes tax and investment information. All this information is used to determine the size of furnace needed and the cost of the system. A user's manual is included with the program.

Summary and Conclusions

Many extra costs and problems are encountered with the decision to use biomass as fuel. "Hidden" costs such as the value of biomass for other purposes, extra machinery and handling costs, and unforeseen labor charges can increase biomass costs significantly. Problems can occur with furnace-feeding devices, especially when a number of different fuels are used. Fire dangers exist because of open fuel lines between

the furnace and the fuel supply. Retrofitting an existing system will not usually return economic rewards because of the cost of adaptation and construction. The system purchased should be matched to the operating conditions without any required modifications. Any system that requires constant supervision during operation will probably never return its investment. The optimum system design should be usable for more than one fuel without causing operating problems. Economic feasibility is best when the biomass used for fuel has little value for any other purpose.

Biomass systems, in general, increase their economic feasibility with extended use. The only savings that can be realized over conventional systems is through the use of cheaper fuel. The more fuel used, the more opportunity for savings. Initial equipment costs become a smaller percentage of the total costs as fuel use is increased. Little (1984) concluded that it was not feasible to purchase a biomass system over a propane system for a 100 acre corn crop. Increasing the crop size to 300 or 500 acres would significantly improve the results of this economic analysis, although probably not yet to the point of feasibility. Little's analysis also was performed using corncobs as the fuel source, a material not abundant in Montana and which possesses relatively high alternative values and high harvesting costs which tends to reduce its feasibility.

For practical purposes, it is difficult to use a biomass furnace for space heating when the system was designed for grain drying because of the difference in size needed for these two purposes. The minimum output of a system designed for grain drying will typically be ten times the amount needed for structural heating. Biomass furnaces have a large thermal inertia and therefore cannot be switched on and off like a conventional furnace. The result is a continuous heat output during operation. For heating a structure it will be necessary to store excess heat obtained from the oversized furnace in some relatively large storage medium for later use. Low overall efficiencies arise as a result of operating the furnace at a low output level and because of heat losses from the storage medium.

Expense Summary

Table 1 is a listing of the project's expenses by category, and shows the amount budgeted and the actual amounts committed.

Table 1. Project Financial Report.

<u>Expenditures</u>	<u>Total \$ Committed</u>	<u>\$ Budgeted</u>
Salaries	9504.14	8000.00
Benefits	518.50	800.00
Repair & Maint.	91.84	-----
Travel	751.22	450.00
Commun.	-----	500.00
Supplies	3109.04	2000.00
Other Services	-----	1000.00
Rent	-----	1000.00
Major Eq.	816.25	-----
Equipment	258.00	2050.00
Indirect Chgs.	3006.79	2640.00
Total	18055.75	18440.00
	Free Balance	\$384.25

Work Schedule

The execution of this project lagged the original schedule from its very beginning. Delays in obtaining a second primary investigator resulted in the project beginning approximately 3 months behind schedule.

Because the project was centered around a grain dryer, actual use of the system was limited to seasonal grain crops. The first drying season came too soon after the actual start of the project to fully take advantage of the experimental opportunities, although valuable operating experience was gained. Delays in obtaining some of the required information was the result.

Many electrical problems with both the microprocessor control system and the furnace system were encountered, resulting in further delays and additional expenses.

Feeding problems with straw were never satisfactorily solved, although several different approaches were considered and some of these attempted. Satisfactory use of straw was seen as an important goal in the research, so an extensive amount of the research time was spent engaged in this effort.

Finally, the resignation of one of the primary investigators eliminated an important resource of knowledge and familiarity with the biomass system. Subsequent research had to be conducted without this resource, probably resulting in even greater delays than were already encountered.

Appendices

Note: Many of the sections included in the appendices were reprinted from previous milestone reports, and contain appendices of their own. These appendices are shown with double labels (i.e., Appendix A from Milestone 4 is contained in Appendix K of this report. It is labeled here as Appendix KA.).

Appendix A. Montana Extension Service Data Sheet

Biomass combustion systems are becoming increasingly popular because of rising conventional energy costs. It is realistically possible to save money by using biomass as an energy source, but both biomass fuel and combustion system aspects must be carefully integrated to produce optimum results.

The primary biomass fuel to be used normally must be plentiful in supply and have little or no alternative value to produce a satisfactory energy source. Sufficient energy content of the material is another necessity. Straw and wood by-products of industry are examples of materials usually satisfying these criteria. Other possible fuel materials may meet one or two of these requirements, but not all of them and so may still not be usable. Alfalfa, for example, is plentiful and contains sufficient energy, but its alternative feeding value far outweighs its possible fuel value. Wet or moldy hay, as another example, has no alternative value but its net energy content is too low for it to be practically used as fuel. All conditions for a material need to be studied before it can be determined suitable as a fuel.

Once the type of fuel to be used has been decided upon, the system chosen to utilize it must be matched to the specific characteristics of the biomass material. Materials like straw produce wrapping and plugging problems with rotating system components, such as furnace feed auger mechanisms. Different problems can arise with other systems and fuels. The manufacturer's specifications on fuel types usable with a particular system should be consulted before purchase of a system is undertaken. It is wise to choose a system design that can be used with more than one type of available fuel to permit variability in fuel sources.

The system chosen should be well matched to the conditions it is to operate under. Biomass direct-combustion systems typically have higher operating efficiencies when they are operated in the higher portion of their output range. The heat required from the furnace should be estimated so that the installation can be sized accordingly. Other system operating considerations are whether a heat exchanger is desired or required, how much extra labor will be needed with the system design, and what other types of equipment will be required to obtain, handle, and/or process the biomass in its usable form.

An important point to note is that biomass systems increase their economic feasibility with extended use. The only savings that can be realized over conventional systems is through the cheaper cost of biomass fuel. The more fuel used, the more opportunity for savings. The initial purchase and installation costs of a biomass system become a smaller percentage of the total costs as fuel use is increased.

A BASIC computer program is available, from either the Montana Department of Natural Resources and Conservation or the Agricultural Engineering Department at Montana State University, that serves as an aid in a preliminary feasibility analysis of purchasing a biomass furnace system instead of a conventionally-fueled furnace system. The program is suitable for an IBM PC or compatible equipment. The economic information output from the program can serve to notify the user whether or not further investigation of the biomass alternative is justified for his situation.

Summary

The amount and type of biomass fuel available must be carefully matched with the combustion and materials handling characteristics of the furnace to produce optimum results. Problems and inefficiencies arise as a result of not matching the combustion system design with the fuel's characteristics and other operating conditions. The economics of biomass systems generally improve as the amount of energy needed from them increases.

Appendix B. User's Manual for BASIC Program

USER'S MANUAL
ECONOMIC FEASIBILITY ASSESSMENT
for an
AGRICULTURAL BIOMASS FURNACE SYSTEM

developed by
Agricultural Engineering Department
Montana State University
Bozeman, Montana 59717
406/994-2275

Introduction

This pamphlet describes a user-interactive computer program that helps an agricultural producer decide if a biomass-fueled system for drying grain or heating a structure may be economically feasible for a particular operation. The program compares fuel and operating costs of biomass vs. conventionally-fueled systems. It calculates three measures of economic performance for use in the decision-making process.

The program is not intended for use in an in-depth analysis for sizing system components or for making final decisions about investment opportunities. Careful assessment of the assumptions used for calculation should be made in determining how well the forecast fits a particular operation. Appropriate parameter values may be changed if desired to improve program performance for a particular situation. The program may be of benefit to those contemplating a biomass-fueled system for either agricultural or non-agricultural purposes.

Economic Indicators

Net Annual Savings:

Annual savings for a biomass-fueled drying system vs. a conventionally-fueled drying system are estimated using Equation 1. Total fuel costs are calculated for both biomass and conventional fuels, and the difference is the annual fuel cost savings for using biomass. Other costs must be included to produce a realistic net annual savings. Additional maintenance and electrical costs are arbitrarily estimated as a percentage of system installation costs. Additional labor costs are based on wage rate, hours needed for furnace operation, and a 1.5 factor to account for additional biomass harvest, transportation, and handling efforts. Annual savings are adjusted for income tax consequences.

$$AS = (DAC - AO) \times (1 - TAXRT) + (TAXRT \times DC) \quad (\text{Equation 1})$$

where:

AS = Annual savings of biomass fuel, adjusted

AF = Cost to install system, \$

AE = $(.01 \times AF)/3$ = Electricity estimate \$

AL = $WAGE \times 2 \times DAYS$ = Labor estimate \$ (2 hours/day assumed)

AM = $(.04 \times AF)/3$ = Maintenance estimate \$

AO = $AE + AL + AM$ = Total additional overhead for biomass system \$

DAC = Direct annual fuel savings \$, calculated from relative fuel costs

DAYS = Days for drying (input)

TAXRT = Marginal income tax rate (input)

WAGE = Hourly wage rate \$ (input)

DC = Annual straight-line depreciation taken on biomass system, \$

Return on Investment

There are two different ways of examining the return on investment from the program output: an external rate of return on investment and a payback cash flow table. An external return is developed in Equation 2 by comparing tax-adjusted installation costs to annual returns. The annual return is estimated as the annual savings minus the annual straight line depreciation over the life of the system. The computation is adjusted for taxation effects.

The External Rate of Return (ERR) is the interest rate at which the investment will equal, at the end of the investment's life, the total annual savings derived from the investment, provided the annual savings are invested at the current market interest rate. The ERR can then be compared with the alternative effective return obtained from investing the initial system cost at the market rate to determine which investment is more desirable. If the ERR is higher than the market rate, then the biomass system investment is more desirable than investing at the market interest rate. If the output ERR is negative, it is usually more instructive to observe the payback cash flow table as an indication of how the economic returns will appear. It would never be advisable to make an investment with a negative ERR. An Economics text should be consulted for further clarification.

$$INV(1 + i')^N = FW \times AS \quad (\text{Equation 2})$$

where previously undefined variables are:

INV = initial investment

i' = ERR

N = life of investment

FW = future worth factor (at time N) of the series of AS payments

The program solves for the value of i' that satisfies Equation 2.

Payback Period and Cash Flows

A payback period is determined by deducting tax credits and annual returns from principal and interest expenses on the installed system. The outstanding balance is carried forward and the process repeated for the life of the system, generating a cash flow table. If the payback period is less than or equal to half the estimated life of the proposed system, the investment could generally be considered profitable. Check with the IRS for current rules regarding investment tax credits or credits for installing alternative energy systems.

Benefit to Cost Analysis

An economic Benefit/Cost ratio for an installation is determined as shown in Equation 3 by comparing the present value of the total annual savings determined in Equation 1 to system installation costs adjusted for investment tax credits.

$$BC = AS \times PW/RF$$

(Equation 3)

where:

PW = present worth factor (brings the total of the AS series back to a single present amount, using an input interest rate)

RF = real fixed system equipment and installation cost

The B/C ratio is the preferred analysis for an indication of project profitability. If BC is less than 1.0, than the investment is not profitable. If BC is greater than 1.0, the investment is profitable.

REQUIRED USER INPUTS (all percentage values are entered as whole numbers)

The program is actually two programs that are intertwined. One branch is taken for grain drying use of the system (input), and the other is taken for structural heating use of the system. The inputs shown below may be required in one or both of the branches.

Name of enterprise

Today's date

Use of system: 1- grain drying, or 2- structural heating

Code number of crop grown

wheat = 1 barley = 2

corn = 3 oats = 4

other = 5

Grain moisture content at harvest, %wb

Grain moisture content for storage, %wb

Acres of grain harvested per season, ac.

Average production, bushels per acre

Allowable actual harvest/drying period, days

Time available to run furnace, hours/day

Size of building to be heated

Extent of insulation (good, fair, or poor)

Average indoor-outdoor temperature difference

Number of days/year furnace system will be used

Code number for comparison fuel

natural gas = 1 #2 fuel oil = 2 propane = 7

#6 fuel oil = 3 electricity = 4

bitum. coal = 5 lign. coal = 6

Cost of comparison fuel, \$/unit

natural gas (MCF) #2 fuel oil (gal) propane (gal)

#6 fuel oil (gal) electricity (kWh)

bitum. coal (ton) lign. coal (ton)

Code number of biomass fuel

grain straw or hay = 1

wood chips or slash = 2

corn stover = 3

Delivered cost per ton of biomass fuel

Moisture content of biomass fuel, %wb

Labor wage rate, \$/hour

Investment tax credit taken on initial cost of biomass system, %

Marginal income tax rate, %

Interest rate on loans, %

Estimated system life, years

Total initial fixed costs for installation (program can also estimate this based on the system's size)

Some Comments on Using the Program

The user of this program should have an understanding of how different inputs affect the program so he can produce the most meaningful analysis and properly interpret its results.

Favorable results usually arise from low labor wage rate inputs and relatively high conventional fuel inputs (generally electricity). For instance, someone who plans to use a biomass fueled furnace to heat his home, previously heated with electricity, can easily show a quick payback period if he enters a zero wage rate for his labor. High fuel use rates, determined primarily by the input average temperature difference (indoor-outdoor) and the number of heating days per year, will further improve the economics of an output.

It is important that the user think through his inputs carefully to make certain that they represent the actual situation. A person who inputs 150 days use of the system/year should not input an average temperature difference over that time of 60 degrees unless the average temperature difference is in fact 60 degrees over the entire 150 days. Most locations in Montana would probably be closer to an average of 30 or 40 degrees over a typical winter.

The user should also realize the implications of his inputs. For instance, even though he can input a zero value for his own labor, this labor is still required and he may not feel his labor is free when harsh ambient conditions are present. Returning to use of the conventional system is a temptation when confronted with having to start up the outdoor furnace in a zero degree snowstorm.

The program is only meant to serve as a general indicator of how the economics of a particular installation might appear. It cannot take into account all factors for all situations, and it can only produce estimates using the factors it does take into account. The user should therefore attempt to produce inputs that are as accurate to his situation as possible so that the inherent error in the output is only due to estimation errors in the program.

The next step to take after obtaining a favorable program output is employing the consultation services of a qualified engineer to receive a more individual analysis.

Appendix C. Example Program Outputs

PRELIMINARY ECONOMIC FEASIBILITY ANALYSIS FOR BIOMASS-FUELED DIRECT-FIRED INCINERATOR FURNACE SYSTEMS

Program development sponsored by
Montana Department of Natural Resources and Conservation

Program developed by
Agricultural Engineering Department
Montana State University
February, 1986

Enterprise name: run 1 4/25/86

=====

PRODUCTION SYSTEM INPUTS

=====

Grain crop grown.....	Corn
Acres harvested.....	300
Production, bu/ac.....	120
Grain moisture content at harvest (%wb)...	33
Grain moisture content for storage (%wb)..	14
Days available to harvest and dry crop....	30
Furnace labor requirement, hours/day.....	13

=====

FUEL USE PARAMETERS

=====

Biomass fuel:	kind used.....	straw or hay
	moisture content (%wb)...	10
	delivered cost per ton, \$	25
Comparison fuel:	kind used.....	propane
	measurement units.....	gal
	cost per unit used, \$....	.7

=====

ECONOMIC PARAMETERS USED FOR EVALUATION

=====

Marginal income tax rate, %	25
Interest rate for loans, %.....	12
Investment tax credit, % of first cost....	10
Labor wage rate, \$/hour.....	5
Expected system life, years.....	10

=====

=====

ESTIMATED EQUIPMENT NEEDS

Consult qualified engineer for system design.

=====

Required furnace capacity, BTU/hour.....	2324866
Required daily grain batch size, bu.....	1200
Grain depth in 20' dia. bin, ft.....	4.77707
Approximate fan horsepower required.....	18.89983
Avg. biomass feed rate, lb/hour.....	304.9005

=====

ECONOMIC EVALUATION SUMMARY

=====

Expected total system installation cost, \$.... 32883.83

Estimated additional costs associated with a biomass-fired system compared to conventional furnace systems.

Maintenance	Electricity	Labor	Total, \$/year
438.4511	109.6128	300	848.0638

Annual cost summary, adjusted for taxes:

Fuel Savings -	Add. Costs +	Depr. =	Annual Return
3884.575	848.0638	3288.383	3099.479

=====

RETURN ON INVESTMENT ANALYSIS

External rate of return on \$ invested: 4.256451

Rate of return on same \$ in money market: 8

=====

PAYBACK PERIOD AND CASH FLOW ANALYSIS

Year	Prin. +	Int. -	Tax Cr. -	ITC -	Returns =	Balance
1	32883	3946	986	3288	3099	29455
2	29455	3534	883		3099	29007
3	29007	3480	870		3099	28518
4	28518	3422	855		3099	27985
5	27985	3358	839		3099	27404
6	27404	3288	822		3099	26771
7	26771	3212	803		3099	26081
8	26081	3129	782		3099	25329
9	25329	3039	759		3099	24509
10	24509	2941	735		3099	23615

=====

BENEFITS TO COSTS ANALYSIS

The benefit/cost ratio is present value of annual returns divided by real fixed costs. Based on current comparison fuel prices, the B/C ratio is .7027352 / 1.00

The required comparison fuel cost would have to be .9500001 \$/unit for breakeven conditions (B/C > 1) to exist.

PRELIMINARY ECONOMIC FEASIBILITY ANALYSIS FOR BIOMASS-FUELED
DIRECT-FIRED INCINERATOR FURNACE SYSTEMS

Program development sponsored by
Montana Department of Natural Resources and Conservation

Program developed by
Agricultural Engineering Department
Montana State University
February, 1986

Enterprise name: run 2 4/25/86

STRUCTURAL HEATING DATA

Building area..... 1500
Extent of insulation..... Well
Average indoor/outdoor temp. difference... 20
Furnace labor requirement, hours/day..... .25
Annual use of furnace, days..... 160

FUEL USE PARAMETERS

Biomass fuel: kind used..... straw or hay
moisture content (%wb)... 10
delivered cost per ton, \$ 35
annual amount used, tons 3.876197
annual cost, \$..... 135.6669
Comparison fuel: kind used..... electricity
measurement units..... kwh
cost per unit used, \$.... .04
annual amount used..... 19244.07
annual cost, \$..... 769.7626

ECONOMIC PARAMETERS USED FOR EVALUATION

Marginal income tax rate, % 0
Interest rate for loans, %..... 12
Investment tax credit, % of first cost.... 0
Labor wage rate, \$/hour..... 0
Expected system life, years..... 10

=====

ESTIMATED EQUIPMENT NEEDS

Consult qualified engineer for system design.

=====

Required furnace capacity, BTU/hour..... 15000
 Average daily heat requirement, BTU..... 360000
 Estimated peak requirement, BTU/hour..... 24000
 Avg. daily biomass fuel use, lb..... 94.42623

=====

ECONOMIC EVALUATION SUMMARY

=====

Expected total system installation cost, \$.... 1500

Estimated additional costs associated with a biomass-fired system compared to conventional furnace systems.

Maintenance	Electricity	Labor	Total, \$/year
20	5	0	25

Annual cost summary, adjusted for taxes:

Fuel Savings -	Add. Costs +	Depr. =	Annual Return
634.0958	25	0	609.0958

=====

RETURN ON INVESTMENT ANALYSIS

External rate of return on \$ invested..... 19.38671
 Rate of return on same \$ invested elsewhere... 8

=====

PAYBACK PERIOD AND CASH FLOW ANALYSIS

Year	Prin. +	Int. -	Tax Cr. -	ITC -	Returns =	Balance
1	1500	180	0	0	609	1070
2	1070	128	0		609	590
3	590	70	0		609	52
4	52	6	0		609	-551

=====

BENEFITS TO COSTS ANALYSIS

The benefit/cost ratio is present value of annual returns divided by real fixed costs. Based on current comparison fuel prices, the B/C ratio is 2.724723 / 1.00

Appendix D. Computer Program Listing

```

100 REM      ++++++
110 REM      ++
120 REM      ++ ECONOMIC FEASIBILITY OF BIOMASS      ++
130 REM      ++ FURNACE SYSTEM                      ++
140 REM      ++
150 REM      ++ PROGRAMMERS: LEE ERICKSON            ++
155 REM      ++ BRUCE KINZEY                        ++
160 REM      ++ AGRICULTURAL ENGINEERING DEPT.      ++
170 REM      ++ MONTANA STATE UNIVERSITY            ++
180 REM      ++ BOZEMAN MT 59715                    ++
190 REM      ++ 406/994-2275 FEBRUARY, 1986        ++
200 REM      ++++++
210 PRINT " ":PRINT " ":PRINT " ":PRINT " ":PRINT " ":PRINT " "
220 A$="PRELIMINARY ECONOMIC FEASIBILITY ANALYSIS FOR BIOMASS-FUELED"
230 B$=" DIRECT-FIRED INCINERATOR FURNACE SYSTEMS "
240 C$=" "
250 D$=" Program development sponsored by "
260 E$=" Montana Department of Natural Resources and Conservation"
270 F$=" Program developed by"
280 G$=" Agricultural Engineering Department"
290 H$=" Montana State University"
300 I$=" February, 1986"
310 PRINT A$
320 PRINT B$
330 PRINT C$
340 PRINT D$
350 PRINT E$
360 PRINT C$
370 PRINT F$
380 PRINT G$
390 PRINT H$
400 PRINT I$
410 PRINT " ":PRINT " ":PRINT " ":PRINT " ":PRINT " ":PRINT " ":PRINT " "
420 PRINT "Enter name of enterprise:"
430 INPUT J$: PRINT " ":PRINT " "
440 PRINT "Enter today's date: e.g. 6/17/1985"
450 INPUT JJ$: PRINT " ":PRINT " "
460 OC=0:NBC=0:AW=0:FW=0:TW=0:AS=0:DC=0: REM CLEARS VALUES FOR RERUN
470 PRINT "Is the biomass furnace to be used for: 1=grain drying,
2=structural"
480 PRINT "heating. Enter appropriate number."
490 INPUT UANS:PRINT " "
500 IF UANS=2 GOTO 4000
510 PRINT "Enter code number of crop grown."
520 PRINT "1 = wheat 4 = oats"
530 PRINT "2 = barley 5 = other "
540 PRINT "3 = corn"
550 INPUT GRAIN:PRINT " "
560 IF GRAIN=1 THEN WT=60: K$=" Wheat "
570 IF GRAIN=2 THEN WT=48: K$=" Barley"
580 IF GRAIN=3 THEN WT=57: K$=" Corn "
590 IF GRAIN=4 THEN WT=37: K$=" Oats "

```

```

600 IF GRAIN=5 THEN WT=50: K$=" Other "
610 PRINT"Answer the following questions to select an appropriate
furnace size."
620 PRINT "
630 PRINT"Enter estimated grain moisture content at harvest:"
640 PRINT"Use percent wet basis."
650 INPUT GMC1:GMC1=GMC1/100:PRINT" "
660 PRINT"Enter desired grain moisture content for storage:"
670 PRINT"Use percent wet basis."
680 INPUT GMC2:GMC2=GMC2/100:PRINT" "
690 PRINT"Enter acres of grain harvested per season:"
700 INPUT ACRES:PRINT" "
710 PRINT"Enter average production, bushels per acre:"
720 INPUT BUAC:PRINT" "
730 PRINT"Enter allowable harvest and drying period, days:"
740 INPUT DAYS:PRINT" "
750 PRINT"Enter time available to operate furnace, hours/day:"
760 PRINT"Note- You will also need time to load/unload bin in
addition"
770 PRINT"to this amount."
780 INPUT HRS: HRS=HRS-2: REM ASSUMED 2HRS REQD TO START/STOP
SYSTEM
790 TOTWT=ACRES*BUAC*WT: REM TOTAL WET GRAIN HARVEST WT, LB
800 WW1=GMC1*TOTWT: REM WATER CONTENT WET GRAIN, LB
810 DW=(1-GMC1)*TOTWT: REM DRY MATTER CONTENT WET GRAIN, LB
820 WW2=GMC2*DW/(1-GMC2): REM WATER CONTENT DRIED GRAIN, LB
830 WTR=WW1-WW2: REM AMOUNT OF WATER TO BE REMOVED, LB
840 WTRHR=WTR/(HRS*DAYS): REM WATER TO BE REMOVED PER HOUR, LB
850 BT=WTRHR*2000: REM ASSUMES 2000 BTU REQD PER LB H2O
REMOVED
860 DBS=ACRES*BUAC/DAYS: REM DAILY DRYER BATCH SIZE REQUIRED, BU
870 DEPTH=DBS*1.25/314: REM GRAIN DEPTH IN 20' DIA BATCH DRYING
BIN
880 HP=.068*12000*DEPTH*1*80*1.5/(330000*.75)
890 REM FAN HP=LB/FT3 AIR x CFM x Depth x "H20/ft grain x 80'
air/'h20 x
900 REM 2.5 system factor/hp constant x fan eff.
910 PRINT" ":PRINT"Approximate drying system characteristics
required:"
920 PRINT;"Consult qualified engineer for detailed design
requirements."
930 PRINT;"Furnace rating, BTU/hour.....";BT
940 PRINT;"Daily dryer batch size, bu.....";DBS
950 PRINT;"Grain depth in 20' dia. drying bin, ft....";DEPTH
960 PRINT;"Approximate fan horsepower requirement, HP";HP
970 REM LP IS LABOR FACTOR BASED ON FURNACE SIZE from Curtis, et.
al.
980 IF BT <= 1E+06 THEN LP = .125
990 IF BT > 1E+06 THEN LP = .25
1000 IF BT > 5E+06 THEN LP = .5
1010 IF BT > 10000000# THEN LP = 1
1020 IF BT > 20000000# THEN LP = 2
1030 IF BT > 40000000# THEN LP = 3
1040 PRINT
1045 PRINT"Answer the following questions to compare biomass and

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```

traditional"
1050 PRINT"fuels as potential grain dryer energy sources.":PRINT" "
1060 PRINT"Enter code number fuel used for comparison:":PRINT" "
1070 PRINT"1= natural gas (MCF) 4= electricity (kwh) 7= propane
(gal)"
1080 PRINT"2= #2 fuel oil (gal) 5= bitum. coal (ton)"
1090 PRINT"3= #6 fuel oil (gal) 6= lignite coal(ton)"
1100 INPUT FU1:REM BE= BURNER EFFICIENCY AND EV= ENERGY VALUE,
BTU/UNIT
1110 IF FU1=1 THEN BE=.778: EV= 1E+06: M$=" Natural gas": N$=" MCF"
1120 IF FU1=2 THEN BE=.825: EV= 1400001: M$=" #2 fuel oil": N$=" gal"
1130 IF FU1=3 THEN BE=.825: EV= 1500001: M$=" #6 fuel oil": N$=" gal"
1140 IF FU1=4 THEN BE=.9: EV= 3413: M$=" electricity": N$=" kwh"
1150 IF FU1=5 THEN BE=.85: EV= 2.7E+07: M$=" bitum. coal": N$=" ton"
1160 IF FU1=6 THEN BE=.8: EV= 1.7E+07: M$=" lig. coal ": N$=" ton"
1170 IF FU1=7 THEN BE=.787: EV= 930001: M$=" propane ": N$=" gal"
1180 PRINT"":PRINT"Enter fuel cost, $/unit. Use appropriate units."
1190 PRINT("$ /MCF, $/gal, $/kwh, $/ton)"
1200 INPUT OC:PRINT" "
1210 IF UANS=2 GOTO 4550
1220 PRINT"Enter code number of biomass fuel to be used:"
1230 PRINT"1 = grain straw or hay"
1240 PRINT"2 = wood chips or slash "
1250 PRINT"3 = corn stover "
1260 INPUT FU2:PRINT" "
1270 IF FU2=1 THEN HV=8600: O$=" straw or hay "
1280 IF FU2=2 THEN HV=8600: O$=" wood products"
1290 IF FU2=3 THEN HV=8600: O$=" corn stover "
1300 PRINT"Enter delivered cost per ton of biomass fuel, $:"
1310 PRINT"Include collection, transportation, and storage costs."
1320 INPUT CO:PRINT" "
1330 PRINT"Enter biomass fuel estimated moisture content, percent wet
basis:"
1340 INPUT MCF:MCF=MCF/100:PRINT" "
1350 IF UANS=2 GOTO 4210: REM RETURN TO STRUCTURAL HEATING SECTION
1360 REM CALCULATE DRY WEIGHT AND WET WEIGHT OF FUEL
1370 DW=1/(1+MCF) : REM BIOFUEL DRY
WEIGHT %
1380 WW=1-DW : REM BIOFUEL WET
WEIGHT %
1390 BW=HV*(1-MCF)-(MCF*1150): REM HEAT AVAILABLE
1400 AEN=BT*HRS*DAY$ : REM THEOR. ANNUAL ENERGY REQD., BTU
1410 AFU2=AEN/(BW*2000) : REM ANNUAL BIOMASS NEEDED, TONS
1420 HFU2=AFU2/(HRS*DAY$): REM HOURLY BIOMASS NEEDED, TONS
1430 HLBFU2=HFU2*2000 : REM HOURLY BIOMASS NEEDED, LBS
1440 ACFU2=AFU2*CO : REM ANNUAL BIOMASS FUEL COST, $
1450 HCFU2=HFU2*CO : REM HOURLY BIOMASS FUEL COST, $
1460 AFU1=AEN/EV*BE : REM ANNUAL COMPARISON FUEL NEEDED, _
UNITS
1470 HFU1=AFU1/(HRS*DAY$): REM HOURLY COMPARISON FUEL NEEDED, _
UNITS
1480 ACFU1=AFU1*OC : REM ANNUAL COMPARISON FUEL COST, $
1490 HCFU1=HFU1*OC : REM HOURLY COMPARISON FUEL COST, $
1500 DHC=HCFU1-HCFU2 : REM DIFFERENTIAL HOURLY FUEL COST
1510 DAC=ACFU1-ACFU2 : REM DIFFERENTIAL ANNUAL FUEL COST

```

```

1520 PRINT"Fuel needs:      Comparison fuel      Biomass fuel  "
1530 PRINT;"
units/hr";TAB(15);HUF1;TAB(35);"tons/hr";HFU2;TAB(35);"lb/hr  ";HLBFU2
1540 PRINT;"      units/yr";TAB(15);AFU1;TAB(35);"tons/yr";AFU2;PRINT" "
1550 PRINT"Fuel costs:      Comparison fuel      Biomass fuel
Difference"
1560 PRINT"
- Bio."
1570 PRINT;" $/hour";TAB(15);HCFU1;TAB(35);HCFU2;TAB(55);DHC
1580 PRINT;" $/year";TAB(15);ACFU1;TAB(35);ACFU2;TAB(55);DAC;PRINT" "
1590 REM
1600 REM  INPUT SYSTEM ECONOMIC PARAMETERS
1610 REM
1620 PRINT"Answer the following questions to evaluate overall economic
feasibility"
1630 PRINT"of a biomass-fueled system as compared to a conventional
system."
1640 PRINT" "
1650 PRINT"Enter labor wage rate, $/hr:"
1660 INPUT WAGE;PRINT" "
1670 PRINT"Enter investment tax credit taken on biomass system, %:"
1680 INPUT ITC;ITC=ITC/100;PRINT" "
1690 PRINT"Enter marginal income tax rate, %:"
1700 INPUT TAXRT;TAXRT=TAXRT/100;PRINT" "
1710 PRINT"Enter interest rate on loans, %:"
1720 INPUT INTRT;INTRT=INTRT/100;PRINT" "
1730 Z=INTRT-.04      : REM  MONEY MKT RATE 4% LESS THAN INT RATE
1740 PRINT"Enter estimated system life, years:"
1750 INPUT LIFE;PRINT" "
1760 IF UANS=2 GOTO 4530:      REM  RETURN TO STRUCTURAL HEATING SECTION
1770 REM
1780 REM  THIS SECTION ALLOWS USER TO INPUT CONSTRUCTION COSTS
1790 REM
1800 PRINT"Do you know the fixed costs for installing the proposed
installation?"
1810 PRINT"1= yes, 2=no":PRINT" "
1820 INPUT TT:ZZ=BT*.0003929:      REM  CALCULATES EQUIV. BOILER
HORSEPOWER
1830 IF TT=2 THEN GOTO 1900
1840 PRINT"Enter total fixed costs for proposed installation, $:"
1850 PRINT"Include components, shipping, installation, site
preparation,"
1860 PRINT"utility installation, consultant or contractor fees, etc."
1870 INPUT AF;PRINT" "
1890 GOTO 1960
1900 AF=ZZ*36:      REM  INSTALLED FIXED COSTS EST'D AT
$36/EBH
1920 PRINT"Installed fixed cost of total biomass system estimated at
$36 per equivalent"
1930 PRINT"boiler horsepower is $:";PRINT AF;PRINT" "
1960 RTF=AF-(AF*ITC): REM  REAL FIXED COST= ACT FIXED COST ADJ FOR INV
CREDIT
b1970 PRINT"Installed fixed costs adjusted for investment tax
credit:";PRINT RTF;PRINT" "
1980 RF=AF-(AF*ITC): REM  ADDITIONAL FIXED COST

```

```

2000 AM=.04*AF/3:      REM ADDITIONAL MAINTENANCE COST AT 4%
INVESTMENT/3
2010 AE=.01*AF/3:      REM ADDITIONAL ELECTRIC COST AT 1% INVESTMENT/3
2020 AL=WAGE*2*DAYS:    REM ADDITIONAL LABOR COST
2030 AO=AM+AE+AL:      REM TOTAL ADDITIONAL COSTS BIOFURNACE VS
CONVENTIONAL
2040 DC=AF/LIFE:        REM ANNUAL STRAIGHT LINE DEPRECIATION CHARGE
2050 PRINT"Estimated additional costs associated with a biomass-fired
system"
2060 PRINT"compared to a conventionally-fired air heating system."
2070 PRINT"Maintenance      Electricity      Labor      Total, $/year"
2080 PRINT;TAB(0);AM;TAB(14);AE;TAB(28);AL;TAB(42);AO:PRINT " "
2090 IF TAXRT=0 GOTO 2140
2100 AS=(DAC-AO)*(1-TAXRT)+(DC*TAXRT): REM (FUEL SAVED-EXTRA+DEPR) ADJ
FOR TAXES
2110 REM AS=ANNUAL SAVINGS, DAC=DIFF. ANNUAL FUEL COST, AO=EXTRA
BIOMASS
2120 REM SYSTEM OP COSTS, DC=ANNUAL SLD DEPRECIATION.
2130 GOTO 2150
2140 AS=DAC-AO:DC=0:      REM ANNUAL SAVINGS WITH TAXRT=0
2150 PRINT"Screen advance halted. Press return to continue.":INPUT
RET:PRINT " "
2160 PRINT"Net annual savings of biomass system over conventional,"
2170 PRINT"considering fuel savings, additional operating costs, and "
2180 PRINT"straight line depreciation, adjusted for tax rate."
2190 PRINT"Fuel Savings - Add. costs + Depr. tax = Net annual returns"
2200 PRINT"          savings"
2210 PRINT;DAC;TAB(15);AO;TAB(28);DC;TAB(38);AS:PRINT " "
2220 IF AS>0 GOTO 2250
2230 PRINT"System will never pay off since annual savings is negative."
2240 GOTO 2590
2250 REM
2260 REM RETURN ON INVESTMENT ANALYSIS
2270 REM ROR= INTEREST RATE WHERE THE FUTURE WORTH OF INVESTMENT =
2280 REM FUTURE WORTH OF ANNUAL SAVINGS @ MONEY-MARKET INTEREST
RATE
2290 FW=((1+Z)^LIFE-1)/Z
2300 XP=1/LIFE
2310 ROR=((AS*FW/RF)^XP-1)*100
2320 RT=((RF*Z)-(RF*Z*TAXRT))/RF*100: REM AFTER TAX RETURN ON MONEY
MARKET INV.
2330 PRINT " ":PRINT " "
2340 PRINT;TAB(15);"RETURN ON INVESTMENT ANALYSIS"
2350 PZ=Z*100
2360
PRINT;"===== ":PRINT " "
2370 PRINT;"Approximate external rate of return on $ invested %:
";ROR
2380 PRINT;"Approximate rate of return for same $ invested elsewhere
%.";PZ
2390 PRINT " "
2400 PRINT"Screen advance halted. Press return to continue.":INPUT
RET:PRINT " "
2410 REM INITIALIZE LOOP VALUES
2420 A=AF      : REM ESTIMATED INITIAL FIXED COSTS

```

```

2430 B=INTRT*A           : REM ANNUAL INTEREST CHARGE ON FIXED COSTS
2440 C=B*TAXRT          : REM TAX CREDIT ON BUSINESS INTEREST
EXPENSE
2450 D=A*ITC            : REM FIRST YEAR INVESTMENT TAX CREDIT
2460 E=AS               : REM ANNUAL SAVINGS (bio vs conv.) FROM
LINE 3130
2470 LB=A+B-C-D-E       : REM LOAN BALANCE OUTSTANDING
2480 PRINT;TAB(15);"PAYBACK PERIOD AND CASH FLOW ANALYSIS"
2490 PRINT;TAB(15);"=====":PRINT" "
2500 PRINT"Year Principal + Interest - Tax Credit - Investment -
Return = Outstanding"
2510 PRINT"              on invest. on interest Tax Credit to
equity balance"
2520 PRINT;"
1";TAB(7);INT(A);TAB(19);INT(B);TAB(30);INT(C);TAB(43);INT(D);TAB(56);IN
T(E);TAB(66);INT(LB)
2530 FOR Y=2 TO LIFE
2540 A=LB:B=INTRT*A:C=B*TAXRT
2550 LB=A+B-C-E
2560 IF A<=0 GOTO 2590
2570
PRINT;Y;TAB(7);INT(A);TAB(19);INT(B);TAB(30);INT(C);TAB(56);INT(E);TAB(66);INT(LB)
2580 NEXT Y
2590 PRINT" "
2600 PRINT"Screen advance halted. Press return to continue.":INPUT
RET:PRINT" "
2610 PWF=((1+Z)^LIFE-1)/(Z*(1+Z)^LIFE) :REM PRESENT WORTH FACTOR
2620 BC=AS*PWF/RF :REM INITIAL BENEFIT/COST
RATIO
2630 REM PWF brings total annual savings for system life back to
present.
2640 PRINT;TAB(15);"BENEFITS TO COSTS ANALYSIS"
2650 PRINT;TAB(15);"=====":PRINT" "
2660 PRINT"B/C ratio is present value of returns divided by real fixed
cost"
2670 PRINT;"B/C =" ;(INT(BC*1000))/1000;"to one";" "
2680 IF BC<1.01 THEN GOTO 2770
2690 IF UANS=2 GOTO 4780
2700 PRINT"Do you want to print out a hard copy of results? (1=yes,
2=no)"
2710 INPUT Q:IF Q=1 THEN GOTO 2950
2720 PRINT"Do you want to rerun the analysis? (1=yes, 2=no)":INPUT T
2730 IF T=1 THEN GOTO 420
2740 END
2750 REM LOOP TO INCREMENT COMPARISON FUEL COST UP TO BREAK EVEN
VALUE
2760 REM
2770 PRINT;"Please wait. Breakeven fuel price calculation in
progress...";" "
2780 OCC=OC
2790 IF FU1<4 THEN OCC=OCC+.05:GOTO 2830 :REM DIFFERENT INCREMENTS FOR
2800 IF FU1=4 THEN OCC=OCC+.001:GOTO 2830:REM DIFFERENT FUELS
2810 IF FU1=7 THEN OCC=OCC+.05:GOTO 2830
2820 OCC=OCC+.25 :REM INCREMENTS COMPARISON FUEL BY
$.25/UNIT

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```

2830 NACFU1=AFU1*OCC      : REM  NEW ANNUAL COMPARISON FUEL COST
2840 NDAC=NACFU1-ACFU2    : REM  NEW DIFFERENTIAL ANNUAL COST OF FUEL
2850 IF TAXRT=0 GOTO 2880
2860 NAS=(NDAC-AO)*(1-TAXRT)+(DC*TAXRT) : REM  NEW ANNUAL SAVINGS
2870 GOTO 2890
2880 NAS=NDAC-AO          : REM  NEW ANNUAL SAVINGS IF TAXRT=0
2890 NBC=NAS*PWF/RF       : REM  RECALCULATE NEW BENEFIT/COST FIGURE
2900 IF NBCK<1.01 THEN GOTO 2790
2910 PRINT"Required comparison fuel cost for breakeven conditions,
$/unit:"
2920 PRINT OCC
2930 GOTO 2690
2940 REM  HARDCOPY PRINTOUT ROUTINE
2950 GMC1=GMC1*100
2960 GMC2=GMC2*100
2970 MCF=MCF*100
2980 TAXRT=TAXRT*100
2990 INTRT=INTRT*100
3000 ITC=ITC*100
3010 Z=Z*100
3020 LPRINT C$;LPRINT C$:
3030 LPRINT;TAB(12);A$
3040 LPRINT;TAB(12); B$
3050 LPRINT;TAB(12); C$
3060 LPRINT;TAB(12); D$
3070 LPRINT;TAB(12); E$
3080 LPRINT;TAB(12); C$
3090 LPRINT;TAB(12); F$
3100 LPRINT;TAB(12); G$
3110 LPRINT;TAB(12); H$
3120 LPRINT;TAB(12); I$
3130 LPRINT C$;LPRINT C$:
3140 LPRINT;TAB(12);"      Enterprise name: "; J$;TAB(55);JJ$
3150 Q$="=====
3160 LPRINT;TAB(12); Q$
3170 LPRINT;TAB(12);"      PRODUCTION SYSTEM INPUTS"
3180 LPRINT;TAB(12); Q$
3190 LPRINT;TAB(12);"Grain crop grown.....";K$
3200 LPRINT;TAB(12);"Acres harvested.....";ACRES
3210 LPRINT;TAB(12);"Production, bu/ac.....";BUAC
3220 LPRINT;TAB(12);"Grain moisture content at harvest (%wb)....";GMC1
3230 LPRINT;TAB(12);"Grain moisture content for storage (%wb)....";GMC2
3240 LPRINT;TAB(12);"Days available to harvest and dry crop....";DAYS
3250 LPRINT;TAB(12);"Furnace labor requirement, hours/day.....";HRS
3260 LPRINT;TAB(12); Q$
3270 LPRINT;TAB(12);"      FUEL USE PARAMETERS"
3280 LPRINT;TAB(12); Q$
3290 LPRINT;TAB(12);"Biomass fuel:      kind used.....";O$
3300 LPRINT;TAB(12);"      moisture content (%wb)....";MCF
3310 LPRINT;TAB(12);"      delivered cost per ton, $";CO
3320 LPRINT;TAB(12);"Comparison fuel: kind used.....";M$
3330 LPRINT;TAB(12);"      measurement units.....";N$
3340 LPRINT;TAB(12);"      cost per unit used, $....";OC
3350 LPRINT;TAB(12); Q$
3360 LPRINT;TAB(12);"      ECONOMIC PARAMETERS USED FOR EVALUATION"

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```

3370 LPRINT;TAB(12); Q$
3380 LPRINT;TAB(12);"Marginal income tax rate, % .....";TAXRT
3390 LPRINT;TAB(12);"Interest rate for loans, %.....";INTRT
3400 LPRINT;TAB(12);"Investment tax credit, % of first cost....";ITC
3410 LPRINT;TAB(12);"Labor wage rate, $/hour.....";WAGE
3420 LPRINT;TAB(12);"Expected system life, years.....";LIFE
3430 LPRINT C$;LPRINT C$;LPRINT ;TAB(12);Q$
3440 LPRINT;TAB(12);" ESTIMATED EQUIPMENT NEEDS"
3450 LPRINT;TAB(12);" Consult qualified engineer for system
design."
3460 LPRINT;TAB(12);Q$
3470 LPRINT;TAB(12);"Required furnace capacity, BTU/hour.....";BT
3480 LPRINT;TAB(12);"Required daily grain batch size, bu.....";DBS
3490 LPRINT;TAB(12);"Grain depth in 20' dia. bin, ft.....";DEPTH
3500 LPRINT;TAB(12);"Approximate fan horsepower required.....";HP
3510 LPRINT;TAB(12);"Avg. biomass feed rate, lb/hour.....";HLBFU2
3520 LPRINT" ":LPRINT" ":LPRINT" ":LPRINT" ":LPRINT" ":LPRINT"
":LPRINT" ":LPRINT" ":LPRINT" ":LPRINT" ":LPRINT" ":LPRINT" ":LPRINT" ":LPRINT" ":LPRINT" ":LPRINT"
3530 LPRINT;TAB(12);Q$
3540 LPRINT;TAB(12);" ECONOMIC EVALUATION SUMMARY"
3550 LPRINT;TAB(12); Q$
3560 LPRINT;TAB(12);"Expected total system installation cost, $....";AF
3590 LPRINT C$
3600 LPRINT;TAB(12);"Estimated additional costs associated with a
biomass-"
3610 LPRINT;TAB(12);"fired system compared to conventional furnace
systems."
3620 LPRINT;TAB(12);"Maintenance Electricity Labor Total,
$/year"
3630 LPRINT;TAB(12);AM;TAB(26);AE;TAB(40);AL;TAB(54);AO
3640 LPRINT" "
3650 LPRINT;TAB(12);"Annual cost summary, adjusted for taxes:
3660 LPRINT;TAB(12);"Fuel Savings - Add. Costs + Depr. = Annual
Return"
3670 LPRINT;TAB(12);DAC;TAB(26);AO;TAB(39);DC;TAB(49);AS;LPRINT" "
3680 LPRINT;TAB(12);"RETURN ON INVESTMENT ANALYSIS"
3690
LPRINT;TAB(12);"=====
:LPRINT" "
3700 LPRINT;TAB(12);"External rate of return on $ invested: "ROR
3710 LPRINT;TAB(12);"Rate of return on same $ in money market: ";Z
3720 LPRINT" "
3730 A=AF : REM ESTIMATED ADDITIONAL INITIAL FIXED
COSTS
3740 B=INTRT*A/100 : REM ANNUAL INTEREST CHARGE ON FIXED COSTS
3750 C=B*TAXRT/100 : REM TAX CREDIT ON BUSINESS INTEREST
EXPENSE
3760 D=A*ITC/100 : REM FIRST YEAR INVESTMENT TAX CREDIT
3770 E=AS : REM LOAN PAYMENT FROM LINE 3130
3780 LB=A+B-C-D-E : REM LOAN BALANCE OUTSTANDING
3790 LPRINT;TAB(12);"PAYBACK PERIOD AND CASH FLOW ANALYSIS"
3800
LPRINT;TAB(12);"=====
:LPRINT" "
3810 LPRINT;TAB(12);"Year Prin. + Int. - Tax Cr. - ITC - Returns =

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```

Balance
3820 LPRINT;TAB(12);"
1";TAB(17);INT(A);TAB(25);INT(B);TAB(32);INT(C);TAB(42);INT(D);TAB(48);I
NT(E);TAB(60);INT(LB)
3830 A=LB
3840 FOR Y=2 TO LIFE
3850 A=LB:B=INTRT*A/100:C=B*TAXRT/100
3860 LB=A+B-C-E
3870 IF A<0 GOTO 3900
3880
LPRINT;TAB(12);Y;TAB(17);INT(A);TAB(25);INT(B);TAB(32);INT(C);TAB(48);IN
T(E);TAB(60);INT(LB)
3890 NEXT Y
3900 LPRINT" "
3910 LPRINT;TAB(12);"BENEFITS TO COSTS ANALYSIS"
3920 LPRINT;TAB(12);"=====;" "
3930 LPRINT;TAB(12);"The benefit/cost ratio is present value of annual
returns"
3940 LPRINT;TAB(12);"divided by real fixed costs. Based on current
comparison"
3950 LPRINT;TAB(12);"fuel prices, the B/C ratio is ";BC;"/ 1.00";
3960 LPRINT;TAB(12);" "
3970 LPRINT;TAB(12);"The required comparison fuel cost would have to
be"
3980 LPRINT;TAB(12);OCC;"$/unit for breakeven conditions (B/C > 1) to
exist."
3990 GOTO 2720
4000 REM STRUCTURAL HEATING CALCULATIONS
4010 PRINT"Enter area (sqft) of building to be heated."
4020 INPUT AREA:PRINT" "
4030 PRINT"Is building: 1=well insulated, 2=fairly insulated, 3=poorly
insulated?"
4040 PRINT"Enter appropriate number."
4050 INPUT INSUL:PRINT" "
4060 IF INSUL=1 THEN KT=.5:I$=" Well"
4070 IF INSUL=2 THEN KT=1:I$=" Fair"
4080 IF INSUL=3 THEN KT=2.5:I$=" Poor"
4090 PRINT"Enter average temperature difference for building (indoor-
outdoor) during"
4100 PRINT"season that furnace will be used, in degrees F."
4110 INPUT DELT:PRINT" "
4120 QHR=AREA*KT*DELT: REM AVERAGE HEAT REQUIREMENT PER HOUR
4130 PQHR=QHR*1.6: REM ESTIMATED PEAK HEAT REQUIREMENT
4140 DQHR=QHR*24: REM AVERAGE DAILY HEAT REQUIREMENT
4150 PRINT"Enter number of hours/day (24hr basis) that you are willing
to spend"
4160 PRINT"stoking, cleaning, etc. the furnace (0.25 hour minimum)."

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```

4240 PRINT"Do you know the biomass system's total equipment and
installation costs?"
4250 PRINT"(1=yes, 2=no)":INPUT IANS:PRINT" "
4260 IF IANS=2 GOTO 4300: REM GO TO COST CALCULATION SECTION
4270 PRINT"Enter the total equipment + installation cost."
4280 INPUT SCOST:PRINT" ":RF=SCOST
4290 GOTO 4440
4300 IF BATCH<200 GOTO 4360
4310 PRINT"Batch size is ";INT(BATCH);" lb. Furnace size will be
relatively large,"
4320 PRINT"but can be decreased by increasing the hours per day you
will spend stoking"
4330 PRINT"it. Do you wish to increase your stoking time? (1=yes,
2=no)"
4340 INPUT SANS:PRINT" "
4350 IF SANS=1 GOTO 4150
4360 ZZ=QHR*.0003929: REM EQUIVALENT BOILER HORSEPOWER
4370 SCOST=ZZ*36: REM SYSTEM COST EST'D AT $36/EBH
4380 IF SCOST<1500 THEN SCOST=1500: REM MINIMUM SYSTEM COST
4390 IF BATCH<200 THEN GOTO 4440
4400 IF BATCH<300 THEN SCOST=SCOST+500:GOTO 4440
4410 SCOST=SCOST+2000
4420 PRINT"System size is large. More insulation and/or more often
furnace"
4430 PRINT"recharges recommended.":PRINT" "
4440 PRINT"Is the furnace to be used for heating a: 1=residence,
2=business-oriented"
4450 PRINT"building?":INPUT TANS:PRINT" "
4460 IF TANS=2 GOTO 1650
4470 PRINT"Enter your minimum acceptable rate of return on invested
funds."
4480 INPUT Z:PRINT" ":Z=Z/100:INTRT=Z
4490 PRINT" Enter the expected life of the system."
4500 INPUT LIFE:PRINT" "
4510 PRINT"Enter the value of your labor ($/hr)."

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```

4670 TAXRT=0:ITC=0
4680 REM TAX CALCULATIONS
4690 AF=SCOST-(SCOST*ITC): REM REAL FIXED COST
4700 RF=AF
4710 DC=AF/LIFE: REM DEPRECIATION
4720 PRINT"Installed fixed costs adjusted for investment tax
credit:":PRINT AF:PRINT" "
4730 AM=.04*SCOST/3: REM MAINTENANCE
4740 AE=.01*SCOST/3: REM ELECTRICITY
4750 AL=TIME*WAGE*USE: REM LABOR
4760 AO=AM+AL+AE: REM TOTAL SYSTEM OPERATING COSTS
4770 GOTO 2050
4780 PRINT"Do you want to print out a hard copy of results? (1=yes,
2=no)"
4790 INPUT Q:IF Q=1 THEN GOTO 4830
4800 PRINT"Do you want to rerun the analysis? (1=yes, 2=no)":INPUT
T:PRINT" "
4810 IF T=1 THEN GOTO 420
4820 END
4830 REM HARDCOPY PRINTOUT ROUTINE
4840 LPRINT C$:LPRINT C$:
4850 INTRT=INTRT*100
4860 ITC=ITC*100
4870 TAXRT=TAXRT*100
4880 MCF=MCF*100
4890 LPRINT;TAB(12);A$
4900 LPRINT;TAB(12); B$
4910 LPRINT;TAB(12); C$
4920 LPRINT;TAB(12); D$
4930 LPRINT;TAB(12); E$
4940 LPRINT;TAB(12); C$
4950 LPRINT;TAB(12); F$
4960 LPRINT;TAB(12); G$
4970 LPRINT;TAB(12); H$
4980 LPRINT;TAB(12); I$
4990 LPRINT C$:LPRINT C$:
5000 LPRINT;TAB(12);" Enterprise name: "; J$;TAB(55);JJ$
5010 Q$="=====
5020 LPRINT;TAB(12); Q$
5030 LPRINT;TAB(12);" STRUCTURAL HEATING DATA "
5040 LPRINT;TAB(12); Q$
5050 LPRINT;TAB(12);"Building area.....":AREA
5060 LPRINT;TAB(12);"Extent of insulation.....":I$
5070 LPRINT;TAB(12);"Average indoor/outdoor temp. difference...":DELT
5080 LPRINT;TAB(12);"Furnace labor requirement, hours/day.....":TIME
5090 LPRINT;TAB(12); Q$
5100 LPRINT;TAB(12);" FUEL USE PARAMETERS"
5110 LPRINT;TAB(12); Q$
5120 LPRINT;TAB(12);"Biomass fuel: kind used.....":O$
5130 LPRINT;TAB(12);" moisture content (%wb)....":MCF
5140 LPRINT;TAB(12);" delivered cost per ton, $":CO
5150 LPRINT;TAB(12);" annual amount used, tons ":AFU2
5160 LPRINT;TAB(12);" annual cost, $.....":ACFU2
5170 LPRINT;TAB(12);"Comparison fuel: kind used.....":M$
5180 LPRINT;TAB(12);" measurement units.....":N$

```

```

5190 LPRINT;TAB(12);" cost per unit used, $....";OC
5200 LPRINT;TAB(12);" annual amount used.....";AFU1
5210 LPRINT;TAB(12);" annual cost, $.....";ACFU1
5220 LPRINT;TAB(12); Q$
5230 LPRINT;TAB(12);" ECONOMIC PARAMETERS USED FOR EVALUATION"
5240 LPRINT;TAB(12); Q$
5250 LPRINT;TAB(12);"Marginal income tax rate, % .....";TAXRT
5260 LPRINT;TAB(12);"Interest rate for loans, %.....";INTRT
5270 LPRINT;TAB(12);"Investment tax credit, % of first cost....";ITC
5280 LPRINT;TAB(12);"Labor wage rate, $/hour.....";WAGE
5290 LPRINT;TAB(12);"Expected system life, years.....";LIFE
5300 LPRINT C$;LPRINT C$;LPRINT ;TAB(12);Q$
5310 LPRINT;TAB(12);" ESTIMATED EQUIPMENT NEEDS"
5320 LPRINT;TAB(12);" Consult qualified engineer for system
design."
5330 LPRINT;TAB(12);Q$
5340 LPRINT;TAB(12);"Required furnace capacity, BTU/hour.....";QHR
5350 LPRINT;TAB(12);"Average daily heat requirement, BTU.....";DQHR
5360 LPRINT;TAB(12);"Estimated peak requirement, BTU/hour.....";PQHR
5370 LPRINT;TAB(12);"Avg. daily biomass fuel use, lb.....";DFU
5380 LPRINT " ":LPRINT " ":LPRINT " ":LPRINT " ":LPRINT " ":LPRINT "
":LPRINT " ":LPRINT " ":LPRINT " ":LPRINT " ":LPRINT " ":
5390 LPRINT;TAB(12);Q$
5400 LPRINT;TAB(12);" ECONOMIC EVALUATION SUMMARY"
5410 LPRINT;TAB(12); Q$
5420 LPRINT;TAB(12);"Expected total system installation cost,
$....";SCOST
5430 LPRINT C$
5440 LPRINT;TAB(12);"Estimated additional costs associated with a
biomass-"
5450 LPRINT;TAB(12);"fired system compared to conventional furnace
systems."
5460 LPRINT;TAB(12);"Maintenance Electricity Labor Total,
$/year"
5470 LPRINT;TAB(12);AM;TAB(26);AE;TAB(40);AL;TAB(54);AO
5480 LPRINT " "
5490 LPRINT;TAB(12);"Annual cost summary, adjusted for taxes:
5500 LPRINT;TAB(12);"Fuel Savings - Add. Costs + Depr. = Annual
Return"
5510 LPRINT;TAB(12);DAC;TAB(26);AO;TAB(39);DC;TAB(49);AS;LPRINT " "
5520 LPRINT;TAB(12);"RETURN ON INVESTMENT ANALYSIS"
5530
LPRINT;TAB(12);"=====
:LPRINT " "
5540 LPRINT;TAB(12);"External rate of return on $
invested.....";ROR
5550 LPRINT;TAB(12);"Rate of return on same $ invested elsewhere...";Z
5560 LPRINT " "
5570 A=AF : REM ESTIMATED ADDITIONAL INITIAL FIXED
COSTS
5580 B=INTRT*A/100 : REM ANNUAL INTEREST CHARGE ON FIXED COSTS
5590 C=B*TAXRT/100 : REM TAX CREDIT ON BUSINESS INTEREST
EXPENSE
5600 D=A*ITC/100 : REM FIRST YEAR INVESTMENT TAX CREDIT
5610 E=AS : REM LOAN PAYMENT FROM LINE 3130

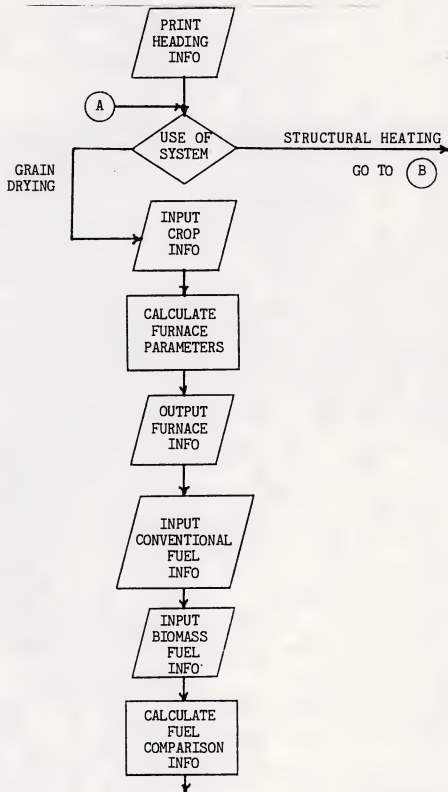
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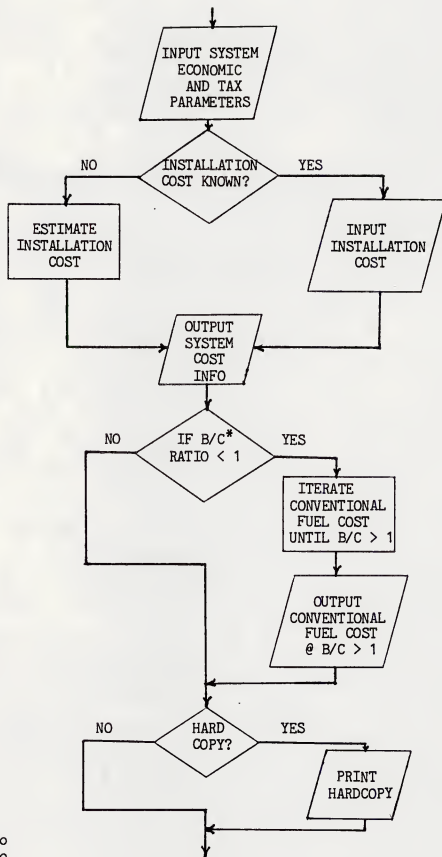
```

5620 LB=A+B-C-D-E           : REM  LOAN BALANCE OUTSTANDING
5630 LPRINT;TAB(12);"PAYBACK PERIOD AND CASH FLOW ANALYSIS"
5640
LPRINT;TAB(12);"=====
:LPRINT" "
5650 LPRINT;TAB(12);"Year  Prin. + Int. - Tax Cr. - ITC - Returns  =
Balance
5660 LPRINT;TAB(12);"
1";TAB(17);INT(A);TAB(25);INT(B);TAB(32);INT(C);TAB(42);INT(D);TAB(48);I
NT(E);TAB(60);INT(LB)
5670 A=LB
5680 FOR Y=2 TO LIFE
5690 A=LB:B=INTRT*A/100:C=B*TAXRT/100
5700 LB=A+B-C-E
5710 IF A<=0 GOTO 5740
5720
LPRINT;TAB(12);Y;TAB(17);INT(A);TAB(25);INT(B);TAB(32);INT(C);TAB(48);IN
T(E);TAB(60);INT(LB)
5730 NEXT Y
5740 LPRINT" "
5750 LPRINT;TAB(12);"BENEFITS TO COSTS ANALYSIS"
5760 LPRINT;TAB(12);"=====;" "
5770 LPRINT;TAB(12);"The benefit/cost ratio is present value of annual
returns"
5780 LPRINT;TAB(12);"divided by real fixed costs. Based on current
comparison"
5790 LPRINT;TAB(12);"fuel prices, the B/C ratio is ";BC;"/ 1.00";
5800 LPRINT;TAB(12);" "
5810 LPRINT;TAB(12);"The required comparison fuel cost would have to
be"
5820 LPRINT;TAB(12);OCC;"$/unit for breakeven conditions (B/C > 1) to
exist."
5830 GOTO 2720

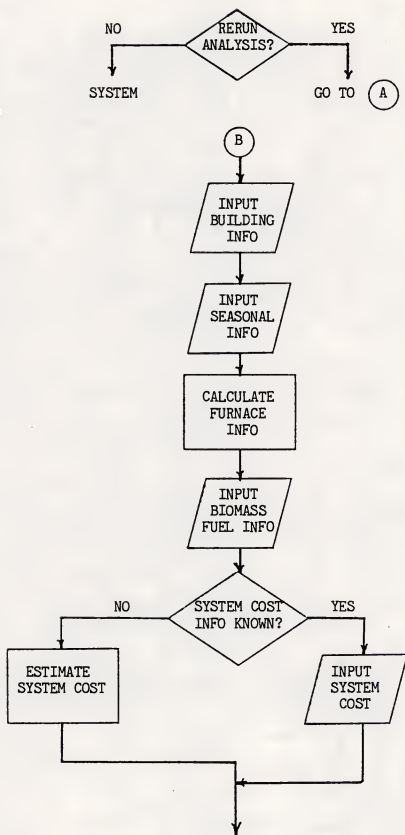
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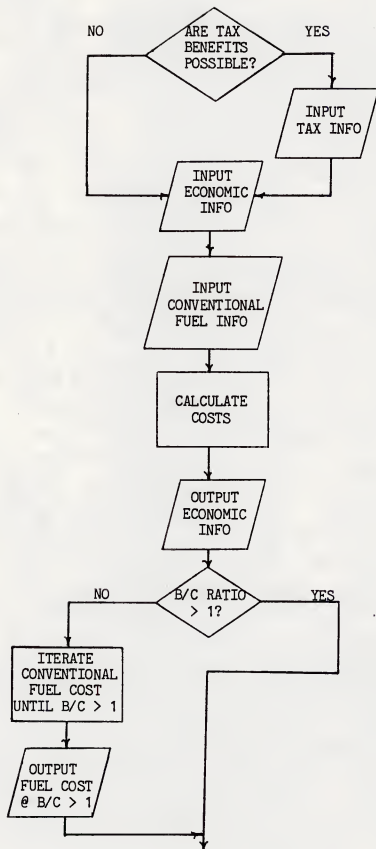
Appendix E. Basic Program Flow Chart

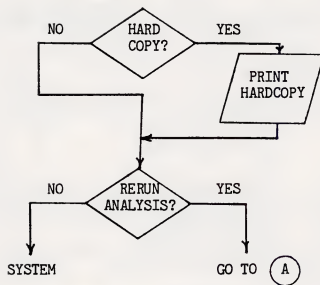




*Benefit to
Cost Ratio







Appendix F. List of Input Values

REQUIRED USER INPUTS (all percentage values are entered as whole numbers)

The program is actually two intertwined programs. One branch is taken for grain drying use of the system (input), and the other is taken for structural heating use of the system. The inputs shown below may be required in only one or both of the branches.

Name of enterprise

Today's date

Use of system: 1- grain drying, or 2- structural heating

Code number of crop grown

wheat = 1 barley = 2

corn = 3 oats = 4

other = 5

Grain moisture content at harvest, %wb

Grain moisture content for storage, %wb

Acres of grain harvested per season, ac.

Average production, bushels per acre

Allowable actual harvest/drying period, days

Time available to run furnace, hours/day

Size of building to be heated

Extent of insulation (good, fair, or poor)

Average indoor-outdoor temperature difference

Number of days/year furnace system will be used

Code number for comparison fuel

natural gas = 1 #2 fuel oil = 2 propane = 7

#6 fuel oil = 3 electricity = 4

bitum. coal = 5 lign. coal = 6

Cost of comparison fuel, \$/unit

natural gas (MCF) #2 fuel oil (gal) propane (gal)

#6 fuel oil (gal) electricity (kWh)

bitum. coal (ton) lign. coal (ton)

Code number of biomass fuel

grain straw or hay = 1

wood chips or slash = 2

corn stover = 3

Delivered cost per ton of biomass fuel

Moisture content of biomass fuel, %wb

Labor wage rate, \$/hour

Investment tax credit taken on initial cost of biomass system, %

Marginal income tax rate, %

Interest rate on loans, %

Estimated system life, years

Total initial fixed costs for installation (program can also estimate this based on the system's size)

Appendix G. Research, Design, and Construction of Controller^{*}

Literature review:

An abundance of useful information can be found on microcomputer-related research for agricultural controls applications in recent American Society of Agricultural Engineers (ASAE) publications. Topics include controls for mobile vehicle data collection, control of environmental systems in structures, control of processing and handling equipment, and a variety of other similar topics.

Most process control systems involve some type of temperature measurement. Summaries of various transducer designs and corresponding system evaluations are readily available (Casell, 1983; Leonard, et al. 1983; Mitchell, 1983a, 1983b). These studies all suggest keeping the design as simple and as inexpensive as possible. This allows use of components that require a minimum of extra parts or support systems to perform adequately.

The kind of Rockwell microcomputer considered for use in this project has been successfully adapted for potato storage control, where it was used to monitor temperature and relative humidity (Rowe, 1984).

Extensive research has been done in the area of signal conditioning and interfacing to the computer (Mitchell, 1982). The few integrated circuit (IC) chips and other electrical components that are required to develop such circuits can be purchased at a fraction of the cost of commercially-built board interface devices. Mitchell gives several suggestions and recommendations on choosing these components.

Corn drying is represented by an equilibrium moisture content equation. The specific temperature and relative humidity of drying air will bring the corn to a particular equilibrium moisture content (Pfost, et al. 1976). It is possible to overdry the first layer of corn in a batch dryer if drying air temperatures are too high. Efficient drying requires a balance between air high temperature for short drying times and low air temperature for relative uniformity of grain moisture content. Some research (Bunn, et al. 1983) has been aimed at computer-controlling the drying air temperature in order to maximize drying efficiency.

^{*} Reprinted from pages 2-11 of Milestone 1 Report, December 5, 1984.

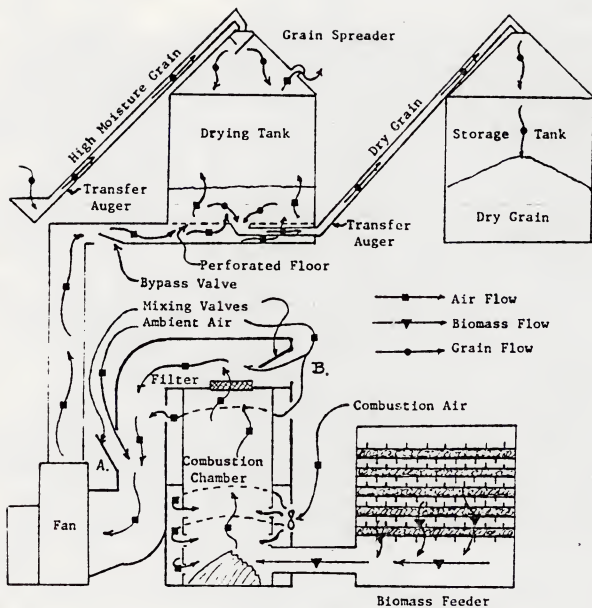


Figure 1. Grain drying system schematic illustration.

Description of current biomass combustion system:

Figure 1 schematically illustrates the biomass furnace system installed and operated at Huntley, MT under the DNRC-MSU agreement RAE 83-1025. This system (Erickson, et al. 1984) was used as the basis for research and design of the microprocessor control system being reported. A basic description of the system and its operation follows.

Biomass fuel is fed to the furnace from a stationary feeder. Beaters on the feeder pull fuel from a bale or stack and deliver it to a horizontal auger. The auger delivers fuel particles into the furnace. Fuel feed rate is controlled by regulation of the fuel delivery hardware.

A manufacturer-supplied control system is used to operate the system. A thermocouple in the top of the furnace chamber is used to monitor combustion temperature. Furnace temperature is compared to an adjustable setpoint on a control panel dial-meter assembly. Fuel is delivered to the furnace if the desired operating temperature setting is below the current exhaust gas temperature level. Fuel will be delivered continuously as long as the temperature remains below this setpoint. When the operating temperature rises above the setpoint temperature, the feeder is shut off and the delivery auger runs for approximately 30 seconds before it also shuts off. The auger stop delay is safety-related, and is intended to break the direct path of fuel between the furnace and the feeder.

There are no automatic controls or regulation devices for the tempered exhaust air used for grain drying. Drying air temperature is manually controlled by adjusting two doors in the air delivery ducting to control the ratio of cool ambient air to hot furnace exhaust. The system operator must monitor temperature in the plenum and make the adjustments necessary to produce the desired drying temperature. The plenum doors are not normally adjusted after the initial setting.

The control system supplied by the manufacturer permits wide fluctuation in the temperature of the drying air. The primary cause for such variation is due to the nature of readily-available Montana-based fuels and how they feed through the existing furnace fuel delivery mechanism. Some fuel remains in the delivery system at the time the temperature setpoint is reached. This fuel and that which is present inside the furnace can carry the furnace exhaust temperature up to 2000°F over the setpoint before peaking.

This control problem can be accentuated by fuels that have irregular geometry, such as straw that has been stored in bales, which do not feed uniformly. They tend to bunch and slug through the system, even though the feed mechanism operates at a uniform rate. High-moisture "tough" fuels, or those with non-uniform moisture contents tend to accentuate this problem.

Problem Statement:

An automatic control system having capability for maintaining a constant drying plenum air temperature is necessary. It should be compatible with and enhance existing system control hardware and strategies. The prototype controller should be able to compensate for variations in furnace exhaust gas temperature. Additional safety-

related fuel delivery hardware features must be incorporated in the existing system in order to allow effective use of the prototype control system.

Controller Design Criteria:

The manufacturer-supplied control system uses an on-off constant-rate fuel delivery system to regulate furnace temperature within approximately $\pm$ or $- 200^{\circ}\text{F}$. Other system variables with potential for use as control parameters include:

1. combustion air flow rate
2. fuel delivery rate control
3. drying air temperature control

Regulation of combustion air is not a good control strategy because the air must be provided in excess to ensure clean combustion. The excess air is heated in the furnace and delivered to the drying plenum, so system efficiency is not adversely affected by this condition.

Control of fuel delivery rate is also an inferior control strategy, because of the variable nature of the fuels used in the system. This approach would require a fuel delivery system that operates continuously at a variable rate. The control function would be stymied if the fuel did not feed uniformly through the system. A fire hazard could exist with this approach at low fuel delivery rates, as an unbroken fuel chain would exist between burner and fuel source.

Biomass fuels burn most efficiently at relatively high temperatures. System performance can be improved by maintaining the furnace temperature at a high level and regulating the drying air temperature. This approach was selected as a portion of the overall system modification for improved automation and control for the following reasons:

1. Good potential existed for developing a reasonably simple, reliable control strategy and associated implementation hardware.
2. Control mechanisms can be developed that will act in a manner complimentary to the existing feed regulation system.
3. Drying air could be regulated independently of the existing control system.
4. The approach is compatible with either direct use of the furnace exhaust or use of a heat exchanger between furnace and heat sink.

System Modifications Required for Successful Control Implementation:

Research to date (Little, 1984) has been directed towards developing a system capable of using readily-available Montana-based agricultural fuels. Since cereal straws are abundant and relatively inexpensive, developing a system that can reliably use straw as a fuel has been a primary development goal.

Other system modifications are necessary in order to benefit from the increased level of system control proposed above. Furnace operations during the 1983 and 1984 seasons were hampered by a significant fire hazard, and by a fuel-induced mechanical breakdown hazard. Both conditions were due primarily to the nature of the existing fuel delivery system and fuels used in the system.

Fire Hazard:

Figure 1 illustrates schematically the direct path between fuel source and furnace. The fuel source caught fire at least twice during 1983-1984 operations due to this direct pathway. One fire was attributed to delivery of excess combustion air to the furnace in conjunction with a high-resistance furnace exhaust gas filter. High air flow induced in the fire chamber by the manufacturer-supplied combustion air fan pushed fire through the path of least resistance back to the fuel source. Another fire was attributed to shutting down the fuel delivery auger before it was totally devoid of fuel. The fire was able to work back up the delivery system into the fuel source.

Mechanical Breakdown Hazard:

Straw stems that have been harvested and baled are of variable lengths and can have over 33% moisture content on a wet basis, depending on storage conditions. Drying or chipping the fuel prior to utilization is a costly and energy-intensive operation that should be avoided if possible. Using baled straw for fuel has resulted in plugging of the furnace delivery auger. High moisture "tough", long-stemmed straw has a tendency to wrap around the feed auger, and can completely plug it up.

Mechanical breakdown hazard can also occur if the fuel delivery system becomes obstructed by foreign matter such as wood, wire, or other items that have been inadvertently baled. An operator must be present during operation of the present furnace system if either of the hazards noted are significant, because mechanical fuel delivery system failures can have serious consequences.

System Modifications for Hazard Mitigation:

The fire hazard condition will be mitigated by incorporating an appropriate fire suppression mechanism and by providing a mechanical break in the fuel delivery chain. The former will be accomplished by attaching a temperature-sensing switch to the furnace feed auger. Temperatures higher than an appropriate setpoint will activate a solenoid-operated water valve. Water will be sprayed into the fuel delivery system until temperatures have been reduced to an appropriate level.

A mechanical break in the fuel delivery system will be provided by switching to a two-stage auger system. The fuel will be delivered from a feed wagon or the existing feeder into a hopper through a vertical drop structure. The hopper assembly will be used to deliver fuel to the furnace through a second auger.

Obstruction of the fuel delivery system can cause the feed auger to seize. A motion-sensing switch on the furnace auger will be used as a monitor for such an event. The motion-sensing switch will serve to shut the system down, should the feeder mechanism become jammed.

Chopped straw or other biomass of uniform size and shape will be used for fuel if necessary in order to ensure desirable furnace stoking characteristics. Emphasis will also be placed on maintaining the fuel at a uniform moisture content in order to promote uniform combustion characteristics. Additional investigations will be done in these areas as stipulated by DNRC as the project progresses.

Incorporation of the features noted above in the existing biomass furnace system will reduce system labor and monitoring requirements. This will allow maximum benefit to be obtained from the automatic control system described in detail below.

Control System Design:

A detailed description of the design of a control system for automatic regulation of the drying air temperature follows.

Air Temperature Measurement:

System fluid temperatures can be monitored with either thermistors or thermocouples. Each provide an electrical signal that is proportional to temperature, which can be conveniently monitored using appropriate signal conditioning and a microcomputer. Thermistor-type transducers were selected for this application because they have a relatively high voltage output, and a generally linear temperature response which is easily converted, calibrated, and interpreted by a computer. They also have no appreciable error caused by electrical connections or stray voltages, as can be the case with thermocouples.

National Semiconductor's ADC 0804 chip was selected as the analog-to-digital converter. It is compatible with microcomputer used, was locally available, and had adequate documentation for interfacing work. The chip converts the analog output of the thermistors to a digital signal that can be read by the computer.

Tempering Door Control:

Drying air temperature should be in the range of 100-150 °F. Regulation is achieved by mixing outside air at ambient temperature with hot exhaust gas at 800-1500 °F from the furnace. The relative location of Doors A and B from the closed position, as shown in Figure 1, will determine air temperature in the plenum.

Motion control of Door A must result in precise, repeatable position control, with no drift, response error over time, or cumulative error effects. A stepping motor was chosen as an appropriate drive mechanism to meet these criteria. Such units rotate a specific angular distance per single voltage pulse input. Multiple pulses are used to achieve a desired number of motor rotations. Motor movement is not time dependent, resulting in accurate and repeatable positioning.

An appropriate stepping motor and control chip were located. Manufacturer's literature is included, and shows required chip-to-motor connections. Refer to Figure 2 and the literature for wiring details. Motor size was determined by back calculating the amount of torque necessary to move the door through the gearing arrangement used. The stepping motor rotates 7.5° for every voltage pulse. It is connected to a roller chain and sprocket assembly that drives the door by rotating bar stock having 12 threads/inch. The resultant overall system gear reduction gives an adjustment sensitivity for the door of $1/576$ inch linear door movement per motor voltage pulse.

The high theoretical degree of door location accuracy is inherent with the motor-gear train assembly. Such accuracy is not entirely necessary in this system, but serves to reduce operating errors by requiring a large number of voltage pulses for appreciable door movement. System response time is slowed, which is an advantage for the furnace system being controlled. Rapid door response would result in continual "hunting" of the control system.

Microprocessor for Control System:

A microcomputer made available in the Agricultural Engineering Department was chosen for the control system. The Rockwell AIM 65 is a versatile unit that can be used in small-scale control systems. It has two 8-bit input/output (I/O) ports and four related control lines, for a total of 20 I/O lines. This unit employs the 6502 microprocessing chip and is programmable in machine language, ASCII Code, or with an optional chip, in BASIC. It contains a thermal head printer, so hard copy can be obtained for program debugging or system monitoring if desired. All memory is volatile except what is initialized at the RESET command.

Overview of Control System:

Control system components and interconnections are shown schematically in Figure 2. Output voltages of the thermistors are converted to digital numbers by the analog/digital converters, which are then read by the microcomputer. Multiple readings are taken and averaged in order to get a reasonable estimate of system temperatures.

A software program calculates the desired door position based on information from the temperature transducers. The desired position is then compared with the current position of the door. The linear difference between actual and desired door positions converted into the number of rotations that the motor must turn in order to move the door the required distance.

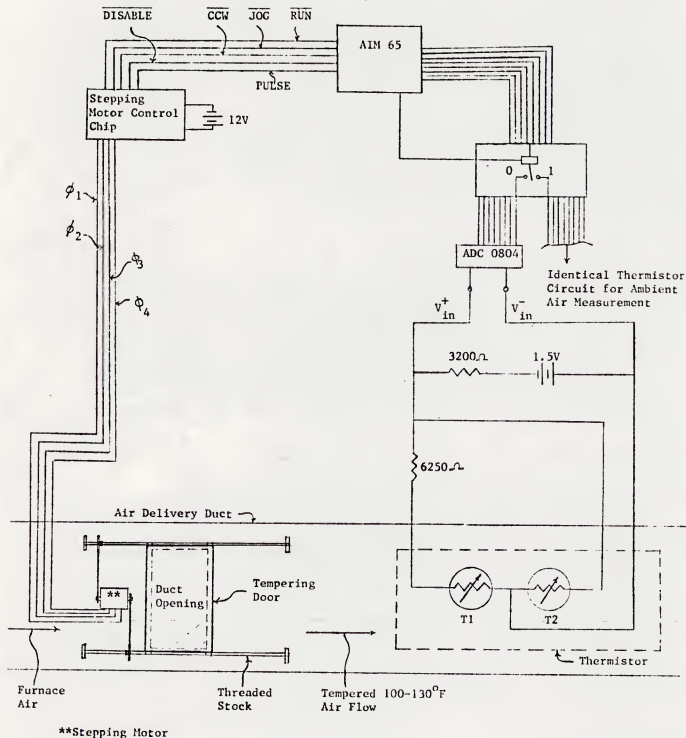


Figure 2. Schematic diagram of computer-controlled tempering air system.

The data collection and programming time requirements and door drive geometry result in a system that will move the door approximately four inches per minute. Time delays are purposely built into the software program to limit system response time. The system continually monitors drying air temperature and adjusts the door as necessary.

Control System Construction, Testing, and Evaluation:

The control system consisting of two thermistor transducers, and AIM 65 microprocessor, Hurst stepping motor and control chip, and door hardware is under development. Construction details, lab and field testing, and system evaluation will be covered in Milestone 2 as stipulated by the DNRC.

Modifications to the biomass furnace fuel delivery system as noted earlier in this report will be completed in conjunction with controller development. The modified system will undergo tests and evaluation in the Spring of 1985.

Appendix G Literature Cited:

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4. Leonard, J.J., J.J.R. Feddes, P.C. Clark, and J.B. McQuitty. 1983. Mini- and micro-computer control of the environment in a broiler barn. *Agricultural Electronics - 1983 and Beyond - Volume II.* pp. 360-369. American Society of Agricultural Engineers, St. Joseph MI.
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Microprocessor Controller Construction:*

Hardware Assembly:

The microprocessor control system that was designed and documented in Milestone 1 has been constructed from commercially-available components. Figure 1 shows the schematic diagram of the system developed. A description of the basic construction procedures follow.

The Rockwell AIM 65 is a stand-alone microprocessor capable of supporting several input-output peripheral devices. It was connected to a Hurst Stepping Motor Control Chip (Part #220001) and the associated Hurst RAS stepping motor as shown in the schematic diagram. Omega OL-705 thermistors were used as the temperature transducers. Manufacturer's information on the thermistors is included. The transducers were connected to the microprocessor via a switching circuit and an ADC 0804 analog-to-digital (a/d) converter chip made by National Semiconductor.

Controller Software Development:

The thermistors used provide a voltage output approximately linearly proportional to temperature changes in the system. As shown by the literature included, thermistor output follows an equation specified by the manufacturer when specific resistor composites are used. An a/d converter is used to change thermistor output into a digital number that the computer can read. The number output by each converter is independent of the empirical manufacturer's equation, but proportional to the transducer voltage output.

Thermistor output was calibrated in order to determine an appropriate performance equation for use in the control system. The transducers were placed in a controlled temperature water bath. Water temperatures used for calibration were held within expected drying system temperature extremes. Data pairs consisting of a/d converter output at known temperatures were collected. Slight variations between successive readings occurred at the same temperature, so averages of 200 thermistor readings taken over about 10 seconds were used for calibration purposes.

Erroneous temperature values were occasionally read during calibration procedures, because the computer was not prevented from reading the RESET value (#255) output by each converter. These data points were thrown out before averaging. Final calibration data points were graphed on x-y coordinates, and a best-fit line was produced. The graphs and corresponding calibration equations are included.

The thermistor calibration equations are used in program software to determine air temperature as a function of thermistor output. This information is used to drive the stepping motor, which positions the air tempering door in an appropriate location. Correct door position depends on air flow rates, exhaust gas temperature, and ambient temperature.

* Reprinted from Milestone 2, pp. 2-6, December 20, 1984.

One of the most important features a system such as the one designed must offer is reliability. Not only must the system be operable in harsh conditions, but it must be able to recover itself in case of power failure or fluctuation. It is desirable to have the system completely self-contained and immediately operable from POWER ON without having to program it manually at every startup. Once the final form of the control program has been written, it will be "burned in" to an EPROM chip, enabling the system to automatically reload the program at every RESET. This will enable the user to simply turn on the system and use the automatic control function immediately. These modifications will increase the user-friendliness of the system, and make it more attractive to inexperienced operators.

B. Equipment Test Scheduling:

Test runs to evaluate the control system, heat exchanger, and various feedstocks will be run in the spring of 1985, and reported under Milestone 3, as stipulated by DNRC. Earlier operation, in conjunction with grain drying activity at Huntley was not feasible during the fall of 1984 for several reasons.

Cool summer growing temperatures and high fall field moisture conditions delayed the corn harvest at Huntley by up to a month, compared with the 1983 growing season. As a result, it was imperative to dry the 1984 corn crop as quickly as possible once harvested. The biomass furnace was operated as it was configured in 1983-4, using straw and stover as fuels for the fall drying season. Some propane fuel was used for drying to evaluate this previously untested backup fuel system. This approach added to the data base and insured timely drying of the harvested grain, valued at \$14,000.

Unforeseen delays slowed control system development and heat exchanger construction. A vendor did not deliver a critical stepping motor for the controller within the specified time. University purchase and competitive bid requirements have slowed procurement of necessary heat exchanger components. The control system is complete at this time, the heat exchanger is under construction, and both are expected to be installed as weather permits in late winter.

Testing and evaluation of the control system can take place independently of grain drying activities. Performance is monitored in terms of temperature of the drying air, and evaluation is based on degree to which the control system can maintain a constant output air temperature as fuel and air inputs vary.

The heat exchanger can be also be initially evaluated independently of the grain drying process. The unit is expected to reduce furnace fuel-use efficiency and improve air quality. The principal performance unknown at this point is how closely the heat exchanger performance will coincide with the design calculations. This relationship and necessary modifications to existing control strategies will be investigated before using the system to dry grain. Such work will also be useful in assessing system potential for use in meeting space heating needs.

It is expected that about six to eight furnace runs will be necessary in order to evaluate performance of the various system configurations. The run categories are anticipated to be as follows:

1. Reference run, using straw or stover fuel as the base fuel and existing controls without the heat exchanger.
2. Control system testing, evaluation, and modification using the reference fuel and the prototype controller without heat exchanger will require 2 - 3 runs.
3. Heat exchanger testing will be accomplished using reference conditions with heat exchanger installed on the furnace. This will be compared to performance under reference conditions.
4. Alternative fuels will be evaluated by comparison to the reference run with 2 - 3 runs required. This test can be done with or without the heat exchanger, depending on whether Condition 1 or Condition 3 is used as the reference.

These tests will be conducted in the spring of 1985 as weather and the schedule of Bruce Kinzey permits. It is anticipated that a mild weather window should occur sometime in February - March, allowing completion of some of these tests. Additional tests as needed will be conducted during the MSU academic quarter break in the spring.

Appendix H. Design and Construction of Heat Exchanger*

Heat Exchanger Development:

The Sukup Company of Sheffield IA was contacted to see if engineering assistance was available for design of an exchanger, and to see if a retrofit unit was available for the existing furnace. Although current Sukup biomass furnace models have a heat exchanger as standard equipment, the company does not offer a retrofit package. They were not particularly interested in assisting with design of a retrofit unit for their older furnace model.

A directory of American industries (Thomas Register, 1984) was consulted to determine if an appropriate commercial heat exchanger vendor could be located. The Thomas Register lists 75-100 companies involved in heat exchanger design, construction, and sales. Few of these deal with smaller air-to-air counterflow units with specifications such as ours, requiring 1.5-2.0 million BTU/hr exchange capacity, 1500 °F high-side temperature, and potential for accumulation of flammable contaminants in the high temperature air stream.

The Enercon Company of Cleveland Ohio appeared to offer products meeting our needs. Their sales engineer was contacted by telephone, and asked to provide a preliminary bid for a heat exchanger, based on the criteria outlined above. This individual indicated that they would provide a stainless steel tube-in-shell unit to meet specifications, with an estimated delivery of four to six months, and an estimated price of \$28,000. Needless to say, this alternative did not appear to be feasible.

Heat Exchanger Design:

The principal investigator in conjunction with Mr. Bruce Kinzey next designed an appropriate heat exchanger using a standard heat transfer text as reference. This complex process required juggling of several important variables in order to satisfy conflicting geometric, power consumption, and exchanger performance criteria.

A counterflow design concept was chosen as having potential for high efficiency. A flat plate configuration was arbitrarily specified as it would be relatively easy to build. The external exchanger geometry was specified such that the unit could slide into the existing furnace tempering air shroud, and such that it could be easily made from standard sheet metal sizes.

An iterative computer-aided design program for a counterflow flat-plate heat exchanger was developed on the spreadsheet software program SuperCalc II as follows:

Equations for air and exhaust gas parameters were developed as a function of temperature. Parameter values were evaluated at the average fluid film temperature.

* Reprinted from Milestone 2, pg. 6-8.

- a. Furnace heat output was specified near the maximum rating for the furnace. Three of four required fluid temperatures were specified, resulting in calculated values for required fueling rate and exit air temperature. Hot fluid flow rate was specified and cold fluid flow rate calculated.
- b. Appropriate fluid parameter values for hot and cold streams were determined based on average calculated fluid temperatures.
- c. Number of ducts and duct dimensions were specified.
- d. Reynolds and Nusselt numbers were determined, allowing calculation of heat transfer rates and frictional power requirements for hot and cold fluid streams.
- e. Required heat exchanger length was determined, based on parameter values calculated previously. Power requirements for intake and exhaust gas streams were determined.

The program required repeated iterations to yield predicted performance values, because some calculated values (i.e. exchanger length) were required in earlier calculations (i.e. Reynolds and Nusselt numbers). The spreadsheet format seemed to work well for evaluation of design alternatives. Modifications were made in the system geometry parameters in order to arrive at a configuration with acceptable performance that had high efficiency for specified operating conditions.

In order to match fan power capabilities of the available drying air and exhaust gas fans, the unit was arbitrarily designed at maximum flows to generate less than 2" water pressure drop in the drying air stream and less than 1" water pressure drop in the exhaust gas stream. Width was specified as less than 24" for system geometric compatibility, and length was specified as preferably eight feet to best utilize standard metal sheet dimensions without requiring special lengths or forming tools.

The approach outlined above resulted in design of a heat exchanger as shown in the blueprints included. Table 1 is an output of the design program showing expected performance of the heat exchanger unit at near-maximum furnace output.

Appendix I. Heat Exchanger and Controller Testing*

The heat exchanger designed and discussed in Milestone 2 has been constructed, and errors and necessary improvements in the design are discussed herein.

A design problem became apparent, as the heat exchanger was constructed with 18 ga. cold-rolled sheet steel. There was a need for some type of structural support between the plates of the exchanger. The sheets of steel were flexible enough to easily deform and sometimes nearly blocked portions of the exhaust ducts. It was believed that the thermal expansion of the plates, along with the forces exerted by high air velocities over them, would have increased this deformation and substantially reduced the exchanger's performance. Spacers were placed between the plates to overcome this problem. The spacers, 8 foot lengths of square tubing, shown in slide 9, were placed in each inlet duct at midspan. The assembly process also deformed some the sheets, and two of the panels required replacement due to their warped condition. Slide 10 shows these warped panels, and slides 11 and 12 show the jig used in forming the individual panels during construction.

Another problem was detected during construction. The exhaust ducts had been designed for a 3/8" spacing, but no consideration was given to the exhaust entrance spacing, where stainless steel caps were to be installed to protect the panels from the high entrance temperature. These caps reduced the entrance area to such an extent that some of the ducts were nearly closed, greatly limiting the gas flow possible without an excessive pressure drop. In addition, the spacer caps intended for separation of the panels were not rigid enough to maintain an accurate distance between the panels. The heat exchanger was subsequently reassembled, using 7/16" spacer rods to maintain the spacing of the exhaust ducts. This in turn produced 3/8" spaces between the stainless steel caps at the exhaust entrance. This gave a more uniform and accurate construction and added considerable strength and rigidity to the design. The joining of the panels is shown in slide 13, and the finished assembly is shown in slide 14.

The exchanger was transported, installed, and painted with a rust preventative at the Huntley Experiment Station during the week of August 4-9. The completed installation is shown in slides 15 and 16.

The heat exchanger performed very well during testing. Airflow through the bin was not substantially reduced (a measured loss of approximately 9.15%), and a desirable drying temperature was easily attained. In addition, the startup time required for the burner was substantially diminished due to the added airflow in the furnace. Only twenty minutes was required before the furnace would satisfactorily hold the set operating temperature, as opposed to an hour or more before the exchanger was installed. The thermal efficiencies of the burner system with and without the heat exchanger were calculated to be 65.1% and 76.0%, respectively. This corresponds to an exchanger thermal efficiency of 85.6%. The heat exchanger dampens out most of the previously mentioned temperature fluctuations, and also notably improves the input air quality. Slide 17 shows smoky exhaust air as it is exited into the atmosphere; exhaust that previously was mixed with fresh air

* Reprinted from Milestone 3, pp. 5-11. (Slides included in Milestone 3)

and vented into the drying bin. This amount of smoke was only present occasionally, and it occurred typically when a wet spot in the fuel was fed into the furnace. The following slide, 18, shows little or no smoke and was taken during the same run at a later period when the fuel was relatively dry. Also visible in these slides is the only problem thus far encountered with the heat exchanger's performance- loose straw adhering to the air entrance due to the air flow into it. This problem could be easily remedied with a hood for the entrance that extended out to the edge of the feed wagon.

C. Automated Control System

The microprocessor-controlled tempering door system has been modified and partially reconstructed since the last Milestone report. The previous door design required a torque too great for the purchased stepping motor. The door assembly was redesigned to reduce this requirement. One lead screw was substituted for the previous two, reducing the accompanying thread friction by 50%. A lesser weight door was also substituted, to reduce inertial forces by reducing the moving mass of the system. Plastic guide tracks for the door were added to insure alignment throughout the door's travel, and these were lubricated with graphite to reduce friction. Finally, a counterweight equal to the weight of the door was added. Slides 19 and 20 show the initial and final assembly, respectively.

A breakdown in the AIM microcomputer resulted in a considerable delay of the test program. Several of the output ports were rendered incapable of producing a "high" signal. A high signal sent to one of these ports only resulted in a level of between 1 and 2 volts at the output connector, which is below the minimum threshold required (2.4v) to be recognized by a peripheral device as a high signal. The microcomputer was subsequently shipped to the service company for repairs.

The computer control system has shown only limited success. The new door assembly was successful in that the motor was able to move the door in either direction (open or close) with equal ease. The response time of the system, however, is too slow to accurately control the rising and declining temperatures in the air duct. It does moderate the temperature extremes, but does not give the desired control. That the door is effective as a tempering device is without question, but it is more suitable for adjusting the overall mean temperature rather than instantaneous spikes. It is now believed that this door could be set in one position by hand and allowed to remain there throughout the drying process, adjusted only as ambient temperatures vary. Results using manual control of the door are shown in Appendix A. This appendix shows the various furnace temperature settings, door opening settings, and accompanying air temperature readings in the air duct. Examination of this table shows that the desired mean drying temperature of 120 to 130 degrees F can be obtained with various furnace and tempering door settings. These settings, however, are not universal and will change with fuel moisture content and ambient air temperatures. The variations of the temperature readings for each door setting were caused by taking the readings at different points in the feeding system's On/Off cycle.

Another possible use for the microprocessor was to control a water valve for extinguishing any flame that made its way out of the auger

feed tube. The intent was to have a safety back-up in case the continuous auger operation modification failed. This fire hazard was no longer a problem, however, due to the sizable draft through the tube caused by the newly added exhaust fan on the heat exchanger. Even when auger motion was halted with fuel present in the feed tube, no fire was ever detected outside of the furnace wall.

The conclusion thus far is that the microprocessor addition to this project has proved unnecessary. It has in fact resulted in a system that is very fragile and unreliable. Attempting to control the system through the use of a microcomputer does not appear feasible at this point. Perhaps simply monitoring the dryer system for informational purposes would have more merit. Relevant data such as the feeding system's On/Off behavior and average drying temperature achieved could be recorded. The limited benefits from a control-type system, however, appear outweighed by the accompanying problems that exist with it.

D. Grain Quality

No grain corn was grown at the experiment station this year, and in fact none could be found anywhere in the immediate area. There was barley grown at the station, but this was already air-dried in the field to its desired moisture content. As a result, no actual drying of grain with the heat exchanger has taken place. However, the grain drying capability of the system has been demonstrated with the evidence that suitable drying temperatures were easily attainable.

Correspondence with the Grain Lab at MSU has revealed that there are no set standards for particulate matter (ash) content in grain. Standard grading methods take into account such factors as moisture content, ergot content, and percent breakage. There is, however, a grade known as "Special" grade for grains that have unusual characteristics. Under this heading, "treated" grains refer to those that are not in their natural form; that is, something is present in the grain that is not due to "natural" circumstances. Corn with a visible layer of ash adhering to it would probably fall into this category, resulting in a lessened value. The actual dollar amount lost due to this condition is to be determined in Milestone 4.

E. Alternative Uses

The heat exchanger option is a necessity for alternative uses of the biomass system, such as heating a farm shop or barn. Air quality in such an application is strictly regulated, and no consideration of these alternative uses could be given to such a system without the application of a heat exchanger, whatever the cost.

Although an alternative use would require a more mobile system than what is installed at Huntley, no major difficulty would be encountered in fulfilling this requirement. All that is essential is a movable furnace and feed wagon that preferably detach and reattach to stationary ducting easily. A separate fan would probably also be desirable, because the amount of air required for grain drying purposes is likely to be several times the amount needed for building ventilation.

A factor to take into account is the biomass system's reliance on a highly mechanical feeding system for operation. The low temperatures

often experienced in Montana's winters are highly conducive to machine failure, and their effects on the feeding system would be no less severe. The wagon could possibly be stored in a part of the structure that was being heated, but this may again entail added trouble and expense.

Another possible problem exists with utilizing a biomass-fueled furnace for these alternative uses. Because of their thermal inertia, biomass furnaces cannot be switched on and off like a natural gas or electrical furnace, but instead must run continuously, with the result that the heated air temperature must be very close to the desired final room temperature. The air temperature could be controlled satisfactorily with the existing system at Huntley; the problem lies in the continuous operation requirement. The fuel wagon would have to be replenished with fuel probably at least once every 36 hours, and possibly more often than that, depending on the fuel batch size, heating requirements, and ambient air temperature. Space requirements would probably rule out much larger batch sizes than one wagon load. This problem may amount to no more than a general "irritation" to a user, but it could have serious consequences under the right conditions.

There is an alternative method of heating that a biomass fueled furnace could be suited for. This method uses a large mass of high density material, such as rock, to store large amounts of heat from a heat source. This stored heat is then removed as needed. A biomass furnace could be operated at full power to heat the material for a period of, for instance, 8 hours, and then be switched off. The amount of heat stored in the material would probably be sufficient to heat a building for several days, depending on the heating requirements of the building. Rock can be obtained relatively inexpensively, and works well in such applications. If the material were pit-stored, no extra building space would be required. Such a system could be very cost-effective, as it would present low overhead and could be utilized in other ways (ie, water pre-heating) as well as structural heating.

Appendix IA: Air duct temperature readings in degrees F with various tempering door positions and furnace settings. Readings spaced approximately 3 minutes apart. Ambient air temperature approximately 70 degrees F.

<u>Furnace Setting</u>	<u>Tempering Door Position</u>	<u>Reading No.</u>	<u>Temperature</u>
800	closed	1	118
		2	137
		3	135
		4	128
		5	<u>123</u>
		Avg	128.2
	open 3 inches	1	120
		2	119
		3	123
		4	115
		5	<u>120</u>
		Avg	119.4
	open 6 inches	1	112
		2	113
		3	107
		4	111
		5	<u>101</u>
		Avg	108.8
900	closed	1	134
		2	124
		3	138
		4	153
		5	<u>139</u>
		Avg	137.6
	open 3 inches	1	133
		2	123
		3	131
		4	115
		5	<u>123</u>
		Avg	125.0
	open 6 inches	1	105
		2	125
		3	110
		4	112
		5	<u>113</u>
		Avg	113.0

Appendix IA: Continued

<u>Furnace Setting</u>	<u>Tempering Door Position</u>	<u>Reading No.</u>	<u>Temperature</u>
1000	closed	1	153
		2	136
		3	148
		4	142
		5	<u>141</u>
		Avg	144.0
	open 3 inches	1	133
		2	131
		3	147
		4	135
		5	<u>129</u>
		Avg	135.0
	open 6 inches	1	126
		2	118
		3	117
		4	124
		5	<u>122</u>
		Avg	121.4

Appendix J. Fuel Storage Tests*

A. Feedstock Storage, Performance, and Evaluation:

The feedstocks used in this study are baled straw, corn stover, sawdust, and wood chips. Slide 1 shows three collections of fuel: uncovered sawdust, covered sawdust, and uncovered corn stover. The corn stover in this photograph has been stored since October '83, and the sawdust piles were added in October '84. A wood chip pile has since been added in August of '85. Slide 2 shows straw stored in the form of large round bales, baled in September '84. Both of these slides were taken in March '85. Table 1 lists the various fuels and their accompanying moisture contents on four different dates.

Straw does not feed into the furnace as easily or as uniformly as the stover, because of its relatively long length and low density. This bridging causes a nonuniform feed rate and the uneven distribution of fuel in the tube leading into the furnace, as has been mentioned in previous milestone reports. If these clumps of straw are near enough the furnace flame when the feed cycle ends, it is possible for the flame to ignite them and burn back along the auger into the feed wagon. A bearing was installed on the feed auger to allow it to run continuously, with the idea that fuel in the feed tube would always be moving towards the flame and thus prevent the fire from leaving the furnace. Problems associated with this bearing will be discussed later.

<u>Fuel*</u>	<u>Location</u>	<u>12/17/84</u>	<u>3/28/85</u>	<u>7/5/85</u>	<u>10/5/85</u>
1	surface	26.89	28.03	25.07	24.44
2	surface	26.89	58.02	51.41	-----
2	center	26.89	40.82	58.95	42.66
3	surface	6.94	46.56	6.51	22.5
3	center	7.53	12.71	7.82	-----
4	surface	7.50	17.23	2.99	5.83
4	center	7.21	16.01	1.28	-----
5	center	----	-----	20.10	12.37

Table 1. Stored fuels and their accompanying moisture contents on a percent wet basis.

* 1-Covered Sawdust, 2-Uncovered Sawdust, 3-Uncovered Stover, 4-Large Round-Baled Straw, 5-Wood Chips

* Reprinted from Milestone 3, pp. 2-5.(Slides included in Milestone 3)

Straw ignites easily and burns quickly and thus causes relatively rapid fluctuations in the furnace temperature. This has relatively little importance, however, as the system has no difficulty sustaining the furnace temperature around a mean value. When using straw, the beaters will operate for approximately 30 to 45 seconds before the temperature in the furnace increases to the thermostat setpoint, and the temperature remains above this setting for approximately 2.5 minutes before more fuel is required. This results in a feed rate of between 3.25 and 4.0 lb/min, depending on moisture content, ambient air temperatures, thermostat setting, and other factors.

Corn stover and wood chips as feedstocks appear to be the best choices. They are the materials the system was designed for. Due to their relatively dense form, they feed easily and uniformly, producing a more nearly linear temperature level in the furnace. There is less problem with clogging or bridging as is associated with straw, and these fuels ignite more slowly and burn longer. These fuels typically require about 30 seconds of beater operation time to bring the furnace temperature back to the thermostat setting, and generally hold this minimum level for approximately 4.5 minutes. This corresponds to a fuel-feeding rate of about 2.9-3.2 lb/min.

The moisture content of these fuels is quite variable. Water introduced because of rain or snow melt is quickly absorbed into the pile. Surface moisture is subsequently evaporated by a warm temperature period or drawn towards the interior of the pile. It was just recently discovered that the base of the stover storage pile was very wet, and the cobs and stems were rotting, as can be seen by the dark color of the stover in slide 3. An open-sided building that kept rain and snow off the pile would reduce the need for a warm drying period prior to fuel utilization and prevent this bottom-layer deterioration. Protection of the fuel from rain and snow may be essential for good performance.

Sawdust feeds satisfactorily if dry, but because of its extremely small particle size, it absorbs and retains moisture in a sponge-like fashion, and is not satisfactory when wet. The covered sawdust moisture content remained almost the same over the 9 month period at a level too high for efficient use (the mc should be less than about 15% wb for good combustion), as can be seen in Table 1. The uncovered sawdust nearly doubled its moisture content, clearly an unsuitable condition. Another problem was discovered in that the high winds often present in the Huntley area had noticeably reduced the size of the uncovered pile. Covered storage appears to be necessary for sawdust, with some method of stirring or mixing it to assure even drying. However, this entails added trouble and expense, and available barn space may be limited. For sawdust to be a viable source of biomass energy will probably require special conditions; ie, a "free" supply of sawdust due to an on-site source, etc.

The heat exchanger's exhaust fan (to be discussed later) increased the air flow through the furnace. As a result, all fuels caused the temperature level to overshoot the thermostat setting, occasionally by as much as 300 degrees F. Slide 4 shows the thermostat setting dial in the control box. The needle with the circle at the end is the thermostat temperature (in 100's of degrees F), and is set at 1000 degrees F. The other needle is the actual temperature, and shows a reading of 1200 degrees F.

Currently, only a small percentage of farms in Montana grow corn for grain. Wood chips are still relatively cheap and easy to obtain, but increased awareness of their availability and use will quickly reduce their supply. In contrast, almost all farms have an excess supply of straw which can be used as an energy source, much of which is lost each year as unused bales deteriorate in the field. Because of the relative abundance of straw in Montana, as compared with corn stover and wood chips, a considerable amount of time and effort has been spent in trying to make the system utilize straw as well as it utilizes these other fuels. Several ideas were considered and tested to overcome the feeding problems mentioned previously.

Another problem was encountered with the system. The auger and beater controls use delay timers. These timers run the feed auger for a short time after the beaters have stopped. The timers did not operate properly and the auger stopped at the same time as the beaters, resulting in material being left in the auger. It was decided that a redesign to allow continuous running of the auger would solve this problem. This required some sort of support bearing on the auger. In the initial design, the auger rested on the floor of the fuel hopper, and the fuel served as a support for the end of the auger. It was believed that running the auger continuously would cause undue wear on the auger blade and premature failure of the drive chain and sprockets. Slide 5 shows the separation of the auger into two sections to permit installation of a bearing, and slide 6 shows the bearing in place. Tests with this first installation showed that binding of the straw was still a problem around the bearing hanger, so the hanger was removed and replaced with a foot underneath the bearing for support. Clogging problems were still evident, so the bearing was moved out of the transition tube towards the rear of the hopper. Slide 7 shows the present form and location of the auger support system.

The auger support bearing had the desired effect of reducing the load and wear on the auger drive chain and sprocket; the auger is easily rotated by hand. However, the improvement in the system's ability to feed straw was less than desired. When relatively small amounts of straw are placed in the auger hopper by the beaters, the auger will effectively clear itself. Its performance is adequate for approximately 95% of the operation time. Occasionally, however, a prohibitively large amount of straw will be torn from the bale and dropped into the hopper. This results in the clogging and bridging problems experienced previously. These problems can be corrected manually by the operator, but the desired condition of complete automation is not satisfied. An actual overload of straw is shown in slide 8. Straw is an important source of biomass energy for Montana, but an auger-type feeding system does not appear to be practical. Probably a more effective type of feeding system for straw would be a conveyor-belt or "Mulkey-Chain" type that has a flat moving surface for the straw. This would eliminate the binding problems for straw altogether. Such systems are used in many coal-fired furnaces, so probably would be equally effective for the other fuels (corn stover, wood chips) as well.

Appendix K: Economics *

Cost of Fuels

The estimated total costs per ton and per million Btu of fuels are shown in Table 1. The calculations and assumptions used to derive these results are contained in Appendix A. These costs require a number of assumptions that may not be typical of any particular location. The results can be varied using different parameters such as estimated tractor use per year, equipment costs, age of equipment, etc. The assumed values are thought to be suitable for representing an average situation in Montana.

"Hidden" costs, such as equipment depreciation calculated on an hourly-use basis, are often not recognized in biomass fuel cost calculations. This error results in artificially low estimated costs for biomass fuels. Nevertheless, based solely on annual fuel costs, the biomass fuels appear to compare favorably with conventional fuels. Additional equipment and labor costs required for biomass are the greatest negative factors affecting these fuels.

* Reprinted from Milestone 4, pg. 2-23.

Table 1. Total Costs of Various Fuels

Fuel	Cost/Ton (\$)	Cost/Million Btu (\$)
Corn Cob/Stover Mixture	81.95	6.50
Straw	48.30	3.50
Propane ¹	-----	6.99
Electricity ²	-----	11.72
Wood Distance From Chips <u>Source (mi)</u>		
0	34.94	2.41
10	40.13	2.77
20	45.31	3.13
30	50.50	3.49
60	66.01	4.56

¹\$0.65/gal, 93000 Btu/gal

²\$0.04/kwh

The energy content (Btu/lb) of specific biomass fuels have been reported at widely differing values. Bomb calorimeter tests on the fuels studied at MSU were used to determine the actual energy contents of these fuels. The results from these tests, as well as estimated net energy contents at three moisture levels are shown in Table 2. The darker numbers in the table show the the energy level of the fuels at typical moisture contents at the time of their collection. As an example, the energy value for straw used in Milestone 3 was obtained from a reference that listed it as 5400 Btu/lb @ 15%mcwb (Johnson, et al. 1951). The results of the calorimeter tests indicate that for the straw used in this study, the value would be at least 1000 Btu/lb greater. Another reference listed wood and wood by-products as having 9000 Btu/lb dry matter, exceeding the MSU calorimeter results by almost 600 Btu/lb (Sumner, et al 1983). The values obtained from the MSU calorimeter determinations were determined from the same fuels used in the study and are therefore used in all relevant calculations.

Table 2. Energy Contents of Various Biomass Fuels (Btu/lb)
From MSU bomb calorimeter determinations.

Moisture Content (%wb)	0	10	20	33
Fuel				
Corn Cobs	7821	6924	6026	4860
Corn Stover	7476	6613	5751	4629
Wood Chips	8416	7459	6503	5259
Straw	7811	6915	6019	4854

Fuel Storage vs. Loss of Fuel

The storage and/or drying of some biomass fuels is necessary prior to their use. Drying is required to avoid poor combustion or supplemental energy inputs during the combustion phase. Morey (1983) found that supplemental heat from a propane torch was required to produce a satisfactory heat output when using corn cobs at their harvest moisture content of 33%. The resulting supplemental propane usage was approximately 10 to 15% of that amount required to dry the corn completely with propane. Little (1984) found a similar propane requirement in his study with the Huntley biomass system while using high-moisture feedstock.

There is a degradation or loss of dry matter in the fuel over time during storage. Richey (1982) found that corn stover stored at 13.9%mc lost 10% of its dry matter after six months, while stover that had been stored at 33.4%mc lost 22.6% of its dry matter over the same time period. Smith (et al. 1983), conducting a study on ventilated vs. unventilated storage piles for corn cobs, found that the net available energy of an unventilated pile was approximately 10% lower than the net energy of a ventilated pile after 9 months of storage. Ventilation was achieved through a fan ducted to the center of the pile. They concluded that the difference in energy content of the piles was mainly due to increased dry matter loss and moisture content in the unventilated pile.

The loss of energy in the storage pile requires the collection of additional fuel to provide the total amount of energy needed, thereby increasing costs. An additional 20% of cob/stover fuel is assumed for the calculations used in Appendix A. This percentage is probably slightly conservative, as Little (1984) determined that the moisture content of the stover at harvest averaged 33%, and the stover would be stored for a period of 12 months before its use. Using the assumptions in Appendix A, the years-end comparison is about \$625 of supplemental propane with 33%mc feedstock vs. \$160 increased annual fuel cost for storing the cob/stover mixture. Thus, if storage space is considered free, approximately \$465/year can be saved by storing the stover over a year instead of using it immediately after harvest with supplemental

propane heat.

Studies with round bales have shown that they also suffer dry matter loss when stored over a period of time. Anderson (et al. 1983) found that storage dry matter losses averaged 14% for alfalfa stored outside over one winter. Verma (et al. 1983) found that ryegrass bales stored outside in Louisiana for 7 months averaged about 29% dry matter losses, and averaged about 33% after 12 months. Losses of approximately 12-15% in round bales could probably be reasonably assumed for storage over one winter in Montana.

The barley harvest at the Huntley Experiment Station occurred near enough to the corn harvest that negligible storage losses can be assumed. The barley straw was dry enough to be used as fuel immediately after baling. Storage of the fuel over a winter, however, as would be the case for using the system for structural heating, would result in some losses and extra fuel would be required to compensate for these.

Wood chip dry matter losses are probably less than those of straw and stover, because of their more compact and rigid structure which better resists mechanical deterioration. Like the straw, storage losses can probably be neglected for grain-drying because only two or three months of storage are necessary to dry the wood chips to an easily combustible moisture content, and grain drying would only occur for an additional month or so. Use of the system for grain drying is assumed in the fuel cost calculations. The "least cost" alternative for the feasibility analysis was thus determined.

Microprocessor Control System Installation and Operating Costs

A microprocessor system was designed and constructed in this study and was determined to not be feasible for the application tested.

The microprocessor attempted to modulate air flow in the air duct to control the drying temperature. An error became apparent with this design. The temperature fluctuations in the air duct which the system was intended to correct are caused by temperature fluctuations in the furnace. The control system was an attempt to correct the "symptom" of the problem, as opposed to the "cause" of the problem. For the SUKUP system at Huntley, more accurate control of the fuel flow into the furnace would be the most likely means for effective output temperature control; however, a significant amount of new components as well as modifications to old ones would be required to accomplish reliable fuel-rate control. The associated costs could be expected to outweigh any observed improvements in performance.

Studies have indicated that it is not practical to "retrofit" the existing system in Huntley. After-market modifications to the system are going to result in some unique adaptation problems. Changing individual parts of a system that were originally designed to operate as a unit can cause further problems. However, some other commercially-available biomass systems do contain microprocessor controls designed and installed by the manufacturer. The microprocessors have been integrally designed into the total system, therefore producing a more optimized finished product. It can be assumed that these microprocessor additions are successful in producing benefits that outweigh the costs.

Heat Exchanger Trade-Offs

It was reported in Milestone 3 that drying the grain with direct-fired biomass combustion products could result in the dried grain being labeled "sample" grade if ash or objectionable odors were noticeable in the batch. Judging a batch to be "sample" grade makes it nonsaleable in the commercial market. The remaining value of "sample" grade corn must be found through alternative uses for it.

There are two primary alternatives to commercially selling the dried grain. The first is its use as livestock feed. If the grain producer has a livestock operation, or is associated with a livestock producer who does not object to using the inferior-grade grain as feed, then the grain can have a value similar to other feed supplies.

Ethanol production represents the second primary alternative use for the dried grain. "Sample" grade grain or other can be used in an alcohol plant with no adverse effects on the ethanol production. Inquiries with two local ethanol plants (AE Montana in Manhattan and Alcotech in Ringling) did not produce any value estimates because neither of these plants use corn. Corn fermentation requires a different yeast than wheat or barley and there is not enough corn available in Montana to justify its use in these plants. However, these operations pay market value for the other grains whether or not they are worth market value (e.g. wheat sprouted in the head), so it is arbitrarily assumed that 85% of market value could be recovered for the corn if it became more readily available for this use.

The cost associated with the addition of the heat exchanger is estimated to be approximately \$3000. This amount was calculated using raw material and processing costs, equipment costs (e.g. fan and motor, electrical parts, etc), and estimated labor requirements for construction and installation of a new heat exchanger. The labor requirements were estimated by the shop technician who constructed the original exchanger. Time estimates for a second heat exchanger were used because it is assumed that several of the problems encountered in reconstruction and installation of the previous system could be avoided in future installations. On a commercial scale, other factors like high volumes or specialized tools could reduce the cost further.

The thermal efficiency of the heat exchanger under the conditions tested was estimated to be 73%. Approximately 37% more fuel will have to be fed through the furnace at this exchanger efficiency to produce the same output of the system without the heat exchanger. A higher fuel-feed rate can obtain equivalent drying times to those of the system without the heat exchanger. The only additional operating costs attributable to the heat exchanger are the electricity for the exhaust fan and the additional fuel required. Cost calculations with accompanying values and assumptions are listed in Appendix C.

The time required to bring the furnace up to a suitable operating temperature was decreased from one hour to twenty minutes with the addition of the heat exchanger. This fact was stated in Milestone 3, the reason being that there is no longer a required warmup period for the purpose of eliminating smoke in the exhaust air. Smoky exhaust air no longer affects the quality of the corn, because it no longer passes through the corn. If the system was capable of operating unattended, approximately 40 minutes of labor would be saved at each startup with the heat exchanger. This labor savings could not be realized, however, with the SARC system in its present form, because the system is not

capable of unattended operation. Nevertheless, drying air can be directed through the drying bin from the moment the furnace is ignited, providing opportunity for another labor savings. The total time required for a drying period is reduced because the corn drying process begins almost immediately after startup, and the required labor is therefore also reduced. Assuming the first 15 minutes of operation are negligible as far as corn-drying effects are concerned, 45 minutes of the previous startup requirement of one hour are still available for drying. The result is that the corn will be dried to the desired moisture content approximately 45 minutes sooner with the heat exchanger than before it was installed.

As shown in Appendix C, operating the system 15.2 hours (one drying cycle) at 10^6 Btu/hr will cost approximately \$21.00 more with the heat exchanger than without it, neglecting the possible difference in dried grain values. This amount was calculated using the savings due to 45 minutes less operating time minus the exhaust fan's electricity and the extra fuel required. This cost for a heat exchanger would be absolutely necessary if the system was used for heating a building or other use where humans or animals might be directly exposed to the heated air. This additional cost is slightly offset when using the system for grain drying, as the heat exchanger safeguards against the possible loss of revenue due to a downgrading of the grain to "sample" grade. The magnitude of this offset is relatively small, and is dependent only on the relatively small difference in grain values.

The feasibility of a heat exchanger retrofit for the Huntley system appears to be similar to that of the microprocessor modification discussed earlier. When the total construction and installation costs, maintenance costs (not estimated here), and operating costs are weighed against the possible benefits, the economic and other efforts do not appear justified. However, commercially-manufactured systems with heat exchangers are available, and the unique costs and problems associated with a retrofitting would not be encountered. The benefits and resulting flexibility of the system with a heat exchanger would probably justify the extra cost in a commercial system.

Mass and Energy Inputs

Figure 1, shown on page 2, shows the mass and energy flow diagram for the biomass grain drying system. This figure is intended to serve as a visual aid in understanding where the inputs, losses, and sequences of events occur in the overall harvesting and drying process. This figure may vary with the individual situation, as different cropping practices may alter the procedures required. No-till farming, for example, will remove the tillage input from the diagram, but will increase the chemical input.

Table 3, following the figure, was taken from data produced by the Heimbichner-Drinkwalter "No Till Corn Silage Demonstration" of 1982, and represents accurate inputs to the Huntley corn crop, according to station superintendent Gil Stallknecht. The data shown in this table is for a no-till corn production, which is becoming increasingly popular in Montana and other states.

Table 3. No Till Seedbed Preparation Costs

	Hrs/ Acre	Purchased Materials		Machinery Costs			Total Costs
		Amt/ Acre	Cost/ Unit	Fuel and Lube	Repair and Maint.	Fixed	
Sprayer	0.25			1.72	0.86	3.42	6.01
Atrazine		2.00	3.00				6.00
Wetagent		0.06	3.60				0.22
Planter	0.25			1.72	6.53	12.90	21.14
Seed Corn							
(XL13)		22.00	1.28				28.16
Counter		14.00	1.18				16.52
18-46-0		46.00	0.25				11.50
18-46-0		18.00	0.25				4.50
Labor	0.50		10.00				5.00
Totals (\$/acre)				3.44	7.39	16.32	99.05

Table 4 uses the machine assumptions in Appendix A, and shows the harvest inputs costs/acre for the corn harvest.

Table 5 shows the various electrical components of the biomass harvest and drying system, and gives their respective horsepower and kilowatt ratings.

Little (1984) estimated the overall system's thermal efficiency to be 76%. Since the addition of the heat exchanger, the overall thermal efficiency of the system has dropped to an estimated 56%, or a 27% reduction due to the heat exchanger. The new overall efficiency was determined using fuel feed rates (Btu in) and temperature and volume of air entering the bin (Btu out). Standard heat exchanger efficiency calculations were difficult to perform because of the inability to obtain reliable entrance and exit temperatures of the exhaust air through the heat exchanger. These varied as a function of the state of the furnace feed rates and were not uniform over the entrance and exit of the heat exchanger. The design efficiency of the exchanger was 89%, so the value determined above indicates not only some probable error in the design assumptions used, but also some noticeable heat effects from the extra structural components that were installed during construction of the heat exchanger. The numbers used in the calculations are included in Appendix C.

Table 4. Harvest Inputs

Machine	Input	Hrs/ Acre	Amount/ Acre	\$/ Acre
Tractor				
	Labor	0.50		5.00
	Fuel and Lube		3.45	3.45
	Repair and Maint.			0.90
	Fixed			2.43
	Subtotal			11.78
Combine				
	Labor	0.50		5.00
	Fuel and Lube		5.83	5.83
	Repair and Maint.			4.50
	Fixed			26.92
	Subtotal			42.25
Forage Wagon				
	Repair and Maint.			0.27
	Fixed			2.41
	Subtotal			2.68
Total (\$/acre)				56.71

Table 5. Electrical Components of the Biomass Harvest/Drying System

Component	Motor HP	KW
40 ft Auger	2.5	1.86
Centrifugal Fan	20.0	14.91
Axial Fan	0.75	0.56
Feed Auger	0.75	0.56
Beaters	1.5	1.12
Grain Bin Augers (2)	0.75 each	0.56
Exhaust Fan (Heat Ex.)	3.0	2.24

Biomass System Economics

Results from calculations of the payback period for the money invested in a biomass system using estimated grain revenues are of questionable validity because of the vast number of assumptions that must be relied upon. Not only are a set of assumptions such as those in Appendix A necessary, but weather behavior, future grain prices, and other highly variable factors (or risks) must also be assumed. A more accurate analysis, producing an equivalent decision, is to assume that the user has already decided to purchase a dryer for his grain, and is considering the biomass alternative. Equivalent annual cost comparisons between the various systems will allow the individual to determine which alternative will result in the least end-of-year costs. In other words, the individual knows that he will have to dry his corn to sell or store it, therefore which type of drying system will accomplish this task at the least cost? Calculations of the equivalent annual costs of the various systems are contained in Appendix B. Table 5 gives the results of these calculations. Appendix B should be consulted regarding questions on the values shown.

Table 5. Equivalent Uniform Annual Costs¹ (EUACs) of Various Drying Systems

System Designed For:	Additional ² Money Required for System	Equivalent Annual Cost
Straw	\$15000	\$2801
Cob/Stover	\$15000	\$6783
Propane	0	\$2273
Electricity	0	\$5325
Wood Chips	\$15000	
Distance From Source (miles)		
0		\$3799
10		\$4061
20		\$4324

¹Does not include costs that are common to all systems, ie, drying fan and bin, aeration fan, grain augers, etc.

²Extra money required for biomass equipment, ie, furnace, feedwagon, installation, etc.

As can be seen in the table, a propane system currently remains the best alternative of all the systems shown, the straw system being second. The principal negating factors with the biomass systems can be seen in the appendices to be the relatively high equipment costs and, not quite so evident, the extra labor costs involved. The costs in the table assume that all systems are capable of unattended operation, a goal which the Huntley system has not yet attained. Including a \$5.00/hr of operation labor cost in the biomass figures, as would be the case with the present Huntley system, will nearly double the straw and wood chips' annual operating costs, and increase by one third that of the cob/stover system. In addition, the cost in the table for straw does not include its collection costs or any alternative value, because it has been assumed that the straw's removal was necessary for cropping practices and is not to be sold. All other assumptions remaining constant, the cost of propane would have to increase by about 25% for its annual operating cost to equal the above straw-burning system's. A future potential for biomass is indicated by these results. Relatively small increases in conventional fuel prices (not at all out of the question by today's standards), along with improved system designs will bring economic feasibility to biomass systems.

Appendix KA. Biomass Fuel Cost Calculations

Collection Costs

All of the following cost and power equations are from Hunt(1977).
Price data were obtained from pricing manuals.

Annual Cost (AC) =
of Equipment

$$(\text{Fixed Cost}\%)P/100 + (\text{Annual Use hrs})\{(\text{Repair \& Maint.}\%)P/\text{hr} + \text{Labor}/\text{hr} + \text{Oil Use}/\text{hr} + \text{Fuel Use}/\text{hr}\}$$

Where P= Purchase Price of Equipment

Example: Tractor Use Cost (60hp diesel, operating at average 40% of rated hp,
P= \$15000, annual use = 500hr)

Fixed Costs:

$$\text{Depreciation} = (P-S)/L = (P-0.1P)/10 = 0.09P/\text{yr}$$

$$\text{Interest on Investment} = (P+S)i/2 = (P+0.1P)(0.08)/2 = 0.044P/\text{yr}$$

$$\text{Taxes} = 0.015P/\text{yr}$$

$$\text{Insurance} = 0.0025P/\text{yr}$$

$$\text{Shelter} = 0.01P/\text{yr}$$

Where S= Salvage Value of Equipment
L= Depreciation Life of Equipment
i= Interest Rate

$$\text{Total Fixed Costs} = (.09 + .044 + .015 + .0025 + .01)P/\text{yr} = 0.1615P/\text{yr}$$

Variable Costs:

$$\text{Repair \& Maint.} = 0.012P/100\text{hr}$$

$$\text{Labor} = \$10.00/\text{hr}$$

$$\text{Fuel} = (60\text{hp})(1 \text{ gal}/8.74 \text{ hphr})(\$1.00/\text{gal}) = \$6.86/\text{hr}$$

$$\text{Oil} = (.012 \text{ gal}/\text{hr})(\$3.50/\text{gal}) = \$0.042/\text{hr}$$

Total Annual Costs:

$$\begin{aligned} \text{AC} = & (.1615/\text{yr})(\$15000) + (500\text{hr}/\text{yr})\{(.012)(\$15000)/100\text{hr} + \$10/\text{hr} + \$0.042/\text{hr} \\ & + \$6.86/\text{hr}\} = \$11773.50/\text{yr} \end{aligned}$$

Total Hourly Cost= (\$11773.50/yr)(1 yr/500hr) = \$23.55/hr

Similar calculations are performed on all harvest equipment. Tables A.1 and A.2 show the results of these calculations.

Table A.1. Fixed Costs of Equipment as %P/yr

Machine	Fixed Cost Dep.	Invest. Interest	Taxes	Insur.	Shelter	Total	P (\$)
Tractor	9.0	4.4	1.5	.25	1.0	16.15	15000
Combine	9.0	4.4	1.5	.25	1.0	16.15	50000
Round Baler, PTO	9.0	4.4	1.5	.25	1.0	16.15	8000
Forage Wagon	9.0	4.4	1.5	.25	1.0	16.15	4500
Hauling Wagon	4.5	4.4	1.5	.25	---	10.65	1200

Table A.2. Variable Costs of Equipment

Machine	Variable Cost R&M per 100hr	Labor \$/hr	Fuel \$/hr	Oil \$/hr	Annual Use hr	Total Cost ¹ per hr
Tractor	.012P	10.00	6.86	.042	500	23.55
Combine	.027P	10.00	11.57	.10	150	89.00
Baler	.031P	-----	-----	-----	100	15.40
F. Wagon	.018P	-----	-----	-----	150	5.66
H. Wagon	.018P	-----	-----	-----	100	1.87

¹{Fixed Cost/yr + (Annual Use){Variable Cost}}/Annual Use

Annual Fuel Requirements

The assumptions used for the calculations are listed in the order in which they are used so as to provide maximum clarity to the reader.

Assume the corn is 30% mc at harvest, and is to be dried to 15%. Assume 300 acres of crop, with a yield of 120 bu/ac.

$$\begin{aligned}\text{Annual Energy} &= (300 \text{ ac})(120 \text{ bu/ac})(67.5 \text{ lb corn/bu})(.151 \text{ lb water/lb corn}) \times \\ &\quad (2000 \text{ Btu/lb water}) \\ &= 729 \text{ million Btu (MBtu)}\end{aligned}$$

Using 2000 Btu/lb water allows for 1150 Btu/lb to evaporate the moisture from the corn, the heat absorbed by the corn (specific heat of corn of 0.5878 Btu/lbm F) for an approximate 70 degree F temperature rise in the corn, and an approximate 75% overall thermal efficiency of the system.

Assume that 30 days are allowed to dry the harvest, with 15 hr/day used as the drying cycle.

$$\text{Size of System} = 729 \text{ MBtu}/(30)(15 \text{ hr}) = 1.62 \text{ MBtu/hr}$$

Required cob/stover amount @ 4745 Btu/lb harvested = 153,635 lb @ 2400 lb/ac = 64 acres, assume 90 acres harvested to account for losses during storage, system thermal efficiency, etc.

Required straw @ 6900 Btu/lb harvested = 105,650 lb @ 660 lb/bale = 160 bale, assume 180 bales collected, minimal losses during storage.

Little (1984) determined that harvesting the extra cob/stover biomass with the corn added approximately 0.135 hr/ac to the harvest time. The harvest rate was determined to be approximately 1 ac/hr, but this rate is unusually slow; higher harvest rates could probably be obtained through experience with harvesting the additional biomass. Assuming a normal harvest time of 2 ac/hr, the time required to harvest the corn and cob/stover biomass is:

$$(90 \text{ acres})(.135 \text{ hr/ac}) + (90 \text{ acres})/(2 \text{ ac/hr}) = 12.15 + 45 \text{ hr} = 57.15 \text{ hr}$$

Assuming the round baler operates at 5 ton/hr, 180 bales would take approximately 12 hrs to bale. It is further assumed that the hauling wagon could remove these bales from the field to their storage area in approximately 10 hrs.

Table A.3 shows the resulting annual collection costs for the cob/stover and straw fuels.

Table A.3. Total Collection Costs of Straw and Cob/Stover Fuels

Fuel Machine	Straw		Cob/Stover	
	hrs req'd	cost (\$)	hrs req'd	cost (\$)
Tractor	22.00	518.10	57.15	1345.88
Combine	----	-----	12.15	1081.35
Baler	12.00	184.20	-----	-----
Forage Wagon	-----	-----	57.15	323.47
Hauling Wagon	10.0	18.70	-----	-----
Total		721.60		2750.70

The costs in Table A.3 will vary greatly with the assumptions used. For instance, it has been assumed that the same 60hp tractor used for baling straw is used for hauling and dumping the forage wagons as they become full. It is very possible that an older tractor, with no further depreciation charges would be used for the forage wagons. The figures in the table would be significantly reduced as a result. Conversely, a more expensive tractor or combine than assumed here would increase the costs. These values are only meant to serve as "ballpark" estimates.

Additional Costs Associated With Using Biomass

There are other costs present when using a biomass furnace that must be included in its annual use costs.

Operation Costs

Labor is required for periodically cleaning the furnace, starting up and shutting down the furnace, cleaning the surrounding area, etc. It is assumed that the following values hold:

Straw- 90min/ton @ \$5/hr= \$7.50/ton

Cob/Stover- 75 min/ton= \$6.25/ton

Opportunity Costs

These costs are money that is foregone because the biomass is used for fuel instead of sold for some other use. Straw can occasionally be sold for \$35/ton baled, it is assumed that the actual profit that can be made is only \$20/ton. A harvested corn field can be rented out for \$35/acre as forage pasture, it is assumed that it retains a value of

\$20/acre after the 2400 lb/acre of biomass has been removed (probably optimistic). Then,

OC Straw= \$20/ton

OC Cob/Stover= $(\$35-20/\text{acre})(1 \text{ acre}/2400 \text{ lb})(2000 \text{ lb}/\text{ton}) = \$12.50/\text{ton}$

Transportation and Handling Costs

It is assumed that the biomass is produced on the site where it is to be used, so that no unusual transportation charges are introduced. Nevertheless, it must be transported from the storage area to the feedwagon and be loaded there, adding another cost to be included in the annual use costs. Loose fuels, like the cob/stover mixture, generally require more trips to load the feedwagon than a similar amount of packaged fuels, like round bales. Assuming it takes an average of 6 minutes per trip to the storage area and back with the tractor (including getting out the tractor and returning it, the costs are:

Straw @ one bale/trip= $(1 \text{ trip}/\text{bale})(3 \text{ bale}/\text{ton})(.1\text{hr}/\text{trip})(\$23.55/\text{hr})$
= \$7.07/ton

Cob/Stover @ 300 lb/trip= $(1 \text{ trip}/300 \text{ lb})(2000 \text{ lb}/\text{ton})(.1\text{hr}/\text{trip})(\$23.55/\text{hr})$
= \$15.70/ton

The additional costs for biomass are tabulated in Table A.4.

Table A.4. Additional Costs/Ton of Using Biomass

Cost Fuel	Opportunity	Operation	Trans. & Hand.	Total
Straw	20.00	7.50	7.07	34.57
Cob/Stover	12.50	6.25	15.70	34.45

Total Fuel Costs/MBtu

Cob/Stover

Collection= $\$2750.70/729 \text{ MBtu} = \$3.77/\text{MBtu}$

Additional= $(\$34.45/\text{ton})(\text{ton}/2000\text{lb})(1\text{b}/6300 \text{ Btu})(1\text{M}) = \$2.73/\text{MBtu}$

Total= $\$3.77 + 2.73 = \$6.50/\text{MBtu}$

Cost/ton= $(\$6.50/\text{MBtu})(2000 \text{ lb}/\text{ton})(6300\text{Btu}/\text{lb}) = \$81.95/\text{ton}$

Straw

Collection= $\$721.60/729 \text{ MBtu} = \$0.99/\text{MBtu}$

Additional= $(\$34.57/\text{ton})(\text{ton}/2000\text{lb})(\text{lb}/6900 \text{ Btu})(1\text{M}) = \$2.51/\text{MBtu}$

Total= $\$2.51 + 0.99 = \$3.50/\text{MBtu}$

Cost/ton= $(\$3.50/\text{MBtu})(2000\text{lb}/\text{ton})(6900\text{Btu}/\text{lb}) = \$48.30$

Note: These costs assume that the biomass system is capable of running unattended. Assuming the system was operating @ 1.6MBtu/hr, a \$5.00/hr extra labor charge would add $\$5/1.6 = \$3.13/\text{MBtu}$ to the above values.

Cost of Wood Chips

The cost of wood chips is highly dependent on the distance that the user is located from the source. The wood chips used in this study were acquired from the mill source in Roundup for \$21.00/truckload. It is assumed that this is an average price. Other assumptions are: 2.5 tons/truckload, 20%mc at collection, 12.5%mc at time of use, \$0.20/mi fuel cost of truck, \$0.20/mi fixed costs of truck, \$10/hr labor for driver, 1 hour of labor required (loading, unloading, etc) + the driving time (50mph) for each load.

Additional Costs are similar to cob/stover's, minus the opportunity cost.

Additional Costs= \$16.53/ton

Table A.5. Wood Chip Fuel Costs Per Ton

One-way Miles to Source	Trans. Cost (round trip) per load	Labor	Total + \$21.00	Cost/ Ton	+ Additional Costs/Ton	\$/ MBtu
0	0	10.00	31.00	13.41	34.94	2.41
5	4.00	12.00	37.00	16.00	37.53	2.59
10	8.00	14.00	43.00	18.60	40.13	2.77
15	12.00	16.00	51.00	22.05	43.58	3.01
20	16.00	18.00	55.00	23.78	45.31	3.13
25	20.00	20.00	61.00	26.38	47.91	3.31
30	24.00	22.00	67.00	28.97	50.50	3.49
60	48.00	34.00	103.00	44.54	66.07	4.56

Appendix KB. Equivalent Uniform Annual Cost (EUAC) Comparisons

It is assumed that the additional equipment needed to burn biomass as fuel (ie, furnace, feedwagon, etc) total \$15000. The costs of the drying bin, centrifugal and aeration fans, and other equipment common to all systems are ignored in these calculations. The purpose of this analysis is to provide **comparison** between the different types of systems under consideration.

A different overall thermal efficiency is assumed for propane and electrical systems, because they do not have the heat loss from the furnace and ducting, and combustion inefficiencies of the biomass fuels.

Conventional Energy Required=

$$(1200 \text{ bu/batch})(67.51 \text{ b/bu})(.5878 \text{ Btu/lbmF})(70\text{F}) = 3.333 \text{ MBtu/batch to heat corn}$$

$$(1200 \text{ bu/batch})(67.51 \text{ b/bu})(.151 \text{ b water/lb corn})(1150 \text{ Btu/lb water}) = 13.97 \text{ MBtu/batch to evaporate water}$$

Assuming an 85% thermal efficiency of system, the total required=
 $(13.97 + 3.333)/.85 = 20.4 \text{ MBtu/batch}$

$$\begin{aligned} \text{Total Conventional Energy Required} &= (20.4 \text{ MBtu/batch})(30 \text{ batch/yr}) = \\ &= 612 \text{ MBtu/yr} \end{aligned}$$

Propane Costs

$$(612 \text{ MBtu/yr})(1 \text{ gal}/93000 \text{ Btu}) = 6581 \text{ gal/yr}$$

$$(6581 \text{ gal})(\$0.65/\text{gal}) = \$4278/\text{yr}$$

Electricity Costs

$$(612 \text{ MBtu/yr})(\text{kWh}/3413 \text{ Btu}) = 179300 \text{ kWh}$$

$$(179300 \text{ kWh/yr})(\$0.04/\text{kWh}) = \$7173/\text{yr}$$

In comparing the conventional energy systems with the biomass systems, it is necessary to assume that the additional money needed for the biomass systems could be invested if a conventional system was purchased. A 10 year life of all systems is assumed, and an interest rate of 8%.

$$\text{Interest Income} = P(A/P, 8, 10) = \$15000(.1490) = \$2235$$

$$10\% \text{ Tax Credit (1st year only)} = (0.1)(\$15000) = \$1500$$

$$\text{Adjusted system 1st cost} = \$15000 - \$1500 = \$13500$$

$$\text{Interest income from investment credit} = \$1500(.149) = \$224$$

$$\text{EUAC Propane} = \$4278 - \$2235 = \$2043$$

$$\text{EUAC Electricity} = \$7173 - \$2235 = \$4938$$

$$\begin{aligned} \text{Extra electricity cost for feedwagon} &= (1.12 + .56\text{kw})(450\text{hr})(\$0.04/\text{kwh}) \\ &= \$30.24/\text{yr} \end{aligned}$$

$$\text{EUAC Straw} = \$2235 + (\$3.50/\text{MBtu})(729 \text{ MBtu}) + \$30.24 - \$224 = \$4593$$

$$\begin{aligned} \text{EUAC Cob/Stover} &= \$2235 + (\$6.50/\text{MBtu})(729 \text{ MBtu}) + \$30.24 - \$224 \\ &= \$6783 \end{aligned}$$

$$\begin{aligned} \text{EUAC Wood Chips (0 miles)} &= (\$2.41/\text{MBtu})(729 \text{ MBtu}) + \$2235 + \$30.24 - \\ &\quad \$224 \\ &= \$3799 \end{aligned}$$

Similarly, for greater distances,

$$\text{EUAC 10 miles} = (2.77)(729) + 2042 = \$4061,$$

$$\text{EUAC 20 miles} = (3.13)(729) + 2042 = \$4324, \text{ etc.}$$

To illustrate the effect of varying assumptions on the EUAC values above, assume that the collection cost of the straw can be omitted as a crop necessity, and that the straw will not be sold if it is not used (possesses no alternative value). Then,

$$\text{Cost of Straw} = \$14.60/\text{ton} = \$1.06/\text{MBtu}$$

$$\text{EUAC Straw} = (729 \text{ MBtu})(\$1.06/\text{MBtu}) + \$2235 + \$30.24 - \$234 = \$2801$$

Or, a difference of $\$4593 - \$2801 = \$1792$ due to the different assumptions made.

It can be seen from comparing the EUACs that, with the assumptions used in these calculations, propane continues to possess the least annual cost and is therefore the best alternative.

Appendix KC. Heat Exchanger Efficiency Calculations

Air Flow

$$m = \text{mass of air/time} = PV/RT$$

From data taken before heat exchanger was installed:

$$m = (1827.7 \text{ lb/sqft})(14256 \text{ cuft/min})/(53.34 \text{ ftlb/lbmR})(522 \text{ R}) \\ = 914.2 \text{ lbm/min}$$

After exchanger installed:

$$m = (1827.7 \text{ lb/sqft})(13398 \text{ cuft/min})/(53.34 \text{ ftlb/lbmR})(540 \text{ R}) \\ = 850.2 \text{ lbm/min}$$

$$\% \text{ change} = (914.2 - 850.2)/914.2 \times 100\% = 7.00\%$$

Or, approximately 7% less air is sent through the bin because of the added pressure drop of the heat exchanger.

Thermal Efficiency

1. Wood Chips @ 12.5%mc ~ 7220 Btu/lb

2.9 lb/min ~ 1.256 MBtu/hr

Air into bin ~ 127.5 degrees F Ambient = 68 degrees F

Temperature rise = 59.5 degrees F

$$Q = (850.2 \text{ lbm/min})(60 \text{ min/hr})(.24 \text{ Btu/lbmF})(127.5 - 68 \text{ F}) = 0.7285 \text{ MBtu/hr}$$

$$\text{Efficiency} = \text{Btu out/Btu in} = .7285/1.256 = .58 \text{ or } 58\%$$

2. Mixture of wood chips and straw ~ 7000 Btu/lb

3.2 lb/min ~ 1.347 MBtu/hr

Air into bin ~ 128.2 degrees F Ambient 70 degrees F

Temperature rise = 58.2 degrees F

$$Q = (850.2)(.24)(58.2) = .7125 \text{ MBtu/hr}$$

$$\text{Efficiency} = .7125/1.347 = .529 \text{ or } 52.9\%$$

$$\text{Average} = (.58 + .529)/2 = .555 \text{ or } 56\% \text{ overall thermal efficiency of}$$

system
The previous system thermal efficiency determined by Little (1984) was 76%

$$\text{Heat Exchanger Efficiency} = .56/.76 = .73 \text{ or } 73\%$$

Operating Costs

$$(1200 \text{ bu})(67.5 \text{ lb/bu})(.151 \text{ lb/lb})(2000 \text{ Btu/lb})/(1.6 \text{ MBtu/hr}) = 15.2 \text{ hr}$$

Assume batch is dried 45 minutes sooner than before exchanger was installed due to the reduction of the previous startup requirement.

The reduction in the thermal efficiency of the system due to the 73% efficiency of the heat exchanger will require

$$1/0.73 = 1.37$$

or approximately 37% more fuel to provide the same heat output as the system without the heat exchanger.

It is assumed that the fuel used is straw.

Heat Exchanger Fan:	(-15.2 hr)(2.24 kw)(\$0.04/kwh)	= -1.36
Centrifugal Fan:	(.75 hr)(14.91 kw)(\$0.04/kwh)	= .45
Feeding System:	(.75 hr)(1.68 kw)(\$0.04/kwh)	= .05
Labor:	(\$5.00/hr)(.75 hr)	= 3.75
Fuel (Straw):	(-.37)(180 lb/hr)(15.2 hr) x (ton/2000 lb)(\$48.30/ton)	= -24.45
Propane*:	(1.69 gal)(\$0.65/gal)(.75)	= 0.83

Total (cost per batch)	= \$20.97
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*The previous propane usage required for startup was 1.69 gal/hr.

If it is assumed that the fuel (straw) possesses no alternative value and is removed from the field for cropping practices, the resulting total cost above becomes -\$ 3.67/batch.

Appendix K References Cited

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The following Milestone report has been prepared to document progress to date on a grant agreement dated March 1, 1984, between the Montana Department of Natural Resources and Conservation (DNRC) and the Agricultural Engineering Department at Montana State University. The DNRC grant agreement number is RAE-84-1042.

Section 1. PURPOSE

The purpose of this grant is to lessen the State's reliance on fossil fuels pursuant to the Title 90, Chapter 4, Part 1, MCA and the Administrative rules adopted thereunder.

Section 2. SCOPE OF PROJECT

The Grantee shall optimize the performance of the experimental biomass burner developed under Grant Agreement ARE-407-831 to dry high-moisture corn. The Grantee shall optimize the use of different feedstocks, develop a microprocessor control system, and investigate different management techniques for improved efficiency and product quality such as fuel storage techniques and the use of a heat exchanger. The Grantee shall also develop microprocessor software and supporting documentation for use in site-specific analysis of similar type projects. The objective of the demonstration and testing, computer program, and economic analysis of the biomass furnace system is to demonstrate to Montana agricultural producers the greater utilization flexibility and economic return for biomass by-products grown on their own farms and ranches. The Grantee shall assemble the data and prepare a comprehensive written report. More specifically, the Grantee shall perform the following tasks that have been organized into a sequence of project milestones. These milestones have been organized to provide the most important information as early as possible so that the study can be terminated if the project does not appear feasible.

Section 3. SUMMARY OF PROGRESS ON MILESTONES

	Date Completed.
Milestone 1. RESEARCH AND DESIGN	December 15, 1984
Milestone 2. CONTROLLER CONSTRUCTION, HEAT EXCHANGER DESIGN, AND DEMONSTRATION PREPARATION.	January 1, 1985
Milestone 3. HEAT EXCHANGER CONSTRUCTION AND TESTING, CONTROL EVALUATION, FEEDSTOCK STORAGE TECHNIQUES.	November 6, 1985
Milestone 4. FUEL STORAGE STUDIES AND ECONOMICS	March 31, 1986
Milestone 5. COMPUTER PROGRAM	April 18, 1986

